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The use of diked dredge sediments has the potential to provide landfill for community development projects. However, the successful realization of this objective requires that proper attention be given to the problems (a) possible surface water pollution by the effluent from the containment area, (b) possible groundwater pollution by leachates from the dredged materials, and (c) stabilization of the soft sediments within the diked area. The results of this investigation indicate that (a) the coagulation and precipitation effects of a promising flocculant will increase the sedimentation rate of dredged material slurries, thereby allowing more fine particles to be removed from the supernatants or a reduction in the retention time required to satisfy given effluent standards, and (b) leachates from dredged sediments in diked containment areas do not appear to cause any serious pollution problems; this latter conclusion is due in large part to the fact that the permeability of most clayey or silty dredged sediments is very low, the underlying soil has a natural ability to remove many of the contaminents, and any reasonable active groundwater can adequately dilute the relatively small amounts of contaminents that are leached through the soils.

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Technical Report No. 2
Stabilization of Dredged Material

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

The need to protect the ecology of the Great Lakes and the other waterways of the United States has led to a variety of problems concerned with the dredging and disposal of increasing volumes of polluted dredge spoil in areas of high population density and industrial development. One commonly used alternative to open water disposal is to place these polluted sediments in diked containment areas to form landfills of marginal value. However, due to the high costs involved, the scarcity of land, and other environmental and economic considerations, these landfills should desirably serve some useful purpose. Accordingly, this study was directed toward evaluating quantitatively the engineering characteristics of dredged materials as they affect their potential usefulness in a landfill.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

SUMMARY

Although diked containment areas can satisfactorily prevent dredged sediments and most of their associated pollutants from reaching the open waters, the use of this disposal practice has the potential to provide landfill for community development projects. However, the successful realization of this objective requires that proper attention be given to the problems (a) possible surface water pollution by the effluent from the containment area, (b) possible groundwater pollution by leachates from the dredged materials, and (c) stabilization of the soft sediments within the diked area. The thrust of this investigation is directed toward evaluating the seriousness of these three problems and advancing various methodologies to enhance their respective solutions. Based on a review and discussion of dewatering methods, ground stabilization techniques, and field treatment processes, together with an assessment of the engineering characteristics of dredged materials, three test programs, (flocculation-sedimentation, sedimentation-leaching, and repeated leaching) were conducted to study (a) the effect of various chemical additives on the flocculation and the sedimentation rate of dredged material slurries, (b) the effect of the most promising additives on improving the engineering properties of the sediments, and (c) the long-term pollution potential of the leachates from both chemically treated and untreated dredged materials. In addition, field observations of several diked disposal sites dictated that a test

program be conducted to investigate the effects of evaporation and/or transpiration on dewatering and strengthening dredged sediments. Also studied and evaluated were various other ground stabilization methods, such as compaction, electro-osmosis, vacuum dewatering, quicklime expansion piles, and freezing.

The results of this investigation indicate that (a) the coagulation and precipitation effects of a promising flocculant will increase the sedimentation rate of dredged material slurries, thereby allowing more fine particles to be removed from the supernatants or a reduction in the retention time required to satisfy given effluent standards, and (b) leachates from dredged sediments in diked containment areas do not appear to cause any serious pollution problems; this latter conclusion is due in large part to the fact that the permeability of most clayey or silty dredged sediments is very low, the underlying soil has a natural ability to remove many of the contaminents, and any reasonable active groundwater can adequately dilute the relatively small amounts of contaminents that are leached through the soils. Since containment areas for dredged sediments are frequently located in low lying swampy areas with poor drainage, reversible (rewetting) effects render some soil stabilization methods ineffective. Furthermore, the soft and wet character of most dredged materials severely limit the application of many other stabilization methods. Within the framework of the limitations that are usually present and with a perspective toward the ultimate usefulness of a dredged material landfill, three procedures are suggested to stabilize dredged sediments in diked containment areas; these are (a) the use of subdikes, surface drainage, and evaporation in conjunction with a premixed lime additive, (b) the use of filter dikes, bottom drainage, and perforated aluminum pipes to accelerate dewatering during the early stages of the deposition process, followed by electro-osmosis in the intermediate stage and compaction in the final stage, and (c) the use of quicklime piles and compaction. The first two methods are primarily applicable to new fills, whereas the third is useful for existing fills. Transpiration by vegetation offers an effective aid in the dewatering process, but the presence of the resulting organic matter in the landfill may be detrimental to its long-term usefulness.

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CHAPTER 1

INTRODUCTION

Environmental constraints and/or economic considerations dictate that large volumes of dredged materials be placed in confined disposal areas. Nationwide this volume currently consists of more than 65 million cubic yards annually, of which approximately 5 million cubic yards is from the Great Lakes region, and the trend toward confined disposal appears to be increasing; in fact, estimates indicate that about 7000 acres of land must be employed each year for this purpose. Since most dredging is performed near urban areas and since land in urban areas is usually very expensive, as well as difficult to locate, landfills of sufficiently high quality to play a positive role in the forthcoming system of urban and regional development would be extremely valuable. However, because dredged materials frequently contain substantial amounts of clay-like and organic materials with high water contents, the effectiveness and economy of landfill operations are often hampered by the time-consuming process of consolidation and the resulting man-made land is usually not of very high quality. Hence, there is a need to investigate stabilization methods by which dredged materials can be used to produce useable land of economic value.

In general, the usefulness of a landfill for industrial or residential construction is judged in large part by its settlement and strength characteristics. Since many dredged materials are known to be essentially organic silts and clays which are very compressible and weak in their natural state, stabilization methods must be sought to improve the engineering properties of this type of soil. Also, since consolidation of these materials often requires appreciable periods of time, it is desirable to investigate techniques whereby this process can be predictably accelerated. These criteria dictate that a promising stabilization procedure must ideally induce a stable soil structure in the sediment while simultaneously enhancing its permeability and consolidation rate; furthermore, it should not increase the pollution hazard of the leachate from the stabilized sediment. Based on an investigation of the engineering properties of polluted maintenance dredgings, Krizek, Karadi, and Hummel (1973) reported that the behavior of most dredged materials of concern in this work are not too different from that of a fine-grained, organic soil, the properties of which could be predicted to some extent by previous testing and experience. The general appearance that maintenance dredgings are wet, soft, and weak is only partially due to their inherent nature; the primary reason for this condition is due largely to the environmental circumstances under which these dredgings are placed, namely, in low lying swampy areas with poor drainage.

Although the chemical decomposition of polluted maintenance dredgings is often quite unique compared to that of most soils, the influence of other major factors, such as water content and density, tends to control their engineering behavior, and the unique chemical nature of the dredgings is usually subjugated to a somewhat minor role. Perhaps the most important factor in determining the usefulness of dredging spoil is its water content and the associated value of dry density. Hence, dewatering is one of the most significant parameters in conditioning the dredgings for subsequent use. Also, the chemistry of the fluids and solids of many dredgings shows that they are rich in plant nutrients, and this is further substantiated by a rapid growth of dense vegetation at many fill sites.

Undoubtedly, dredged materials can be used to construct landfills of sufficient quality to serve certain urban and regional planning projects. For example, landfills of dredged spoil may be readily used for recreational parks, agricultural land, or wild life refuges. In addition, dewatered dredgings may be compacted in a suitable manner to form a landfill which may be suitable for a parking lot, residential construction, or light industrial construction. Krizek, Karadi, and Hummel (1973) investigated several techniques of dewatering, including gravity and vacuum drainage, electro-osmosis, and consolidation under an applied load, and each was found to be technically feasible. Of these techniques, evaporation is probably one of the most useful and economical means for dewatering thin lifts of dredgings. Furthermore, certain modifications to currently used procedures for the disposal of maintenance dredgings seem to offer the promise of considerably improvement in the characteristics of the resulting landfill; such modifications include (a) changing the position of the inflow point for the slurry, thereby allowing some control over the location and distribution of particle sizes, (b) increasing the height of the dikes, thereby enhancing the preloading effect and providing additional storage space, (c) placing a drainage blanket at the bottom of the fill, thereby increasing the drainage rate (provided the blanket is adequately drained), and (d) programming the disposal operation so that relatively thin lifts are placed and allowed to desiccate by gravity drainage and evaporation with or without mechanical compaction before additional spoil is deposited, thereby yielding a moderately dense landfill throughout its entire depth.

The major thrust of this study is to investigate and evaluate various possible physical, physico-chemical, and chemical stabilization methods to enable dredged materials to better serve the above-described intended engineering purpose. Special emphasis is placed on chemical stabilization methods and the effect that these methods may have on the composition of leachates from the resulting landfills (that is, the pollution potential of the chemical additives themselves). In order to accomplish these goals, a review of various feasible dewatering methods is given in Chapter 2. This is followed by a discussion in Chapter 3 of different ground stabilization methods that might be used for dredged materials and a review of potentially applicable field treatment processes. The descriptions and engineering characteristics of the dredged materials used in this study are reported in Chapter 4.

Phase 1 of the laboratory chemical stabilization test series of determining the effectiveness of chemical additives on the flocculation and sedimentation properties of the dredged materials, and the details of this work are presented in Chapter 5. Once the more promising chemical additives were determined in Phase 1, the optimum percentages of each and the extent of the improvement realized in the engineering properties were examined and reported in Chapter 6; in addition, the leachates were analyzed chemically to determine the water quality changes that resulted. Chapter 7 contains the work performed in Phase 3, which consisted of studying the long-term pollution effect of the leachates from both chemically treated and untreated dredged materials by means of repeated-leaching tests.

The results of several series of laboratory and field evaporation tests are presented in Chapter 8, and the effect of transpiration through plant growth on the improvement of the engineering properties of dredged materials in a landfill is reported in Chapter 9. Several other ground stabilization methods, such as compaction, electro-osmosis, vacuum dewatering, quicklime expansion pressure stabilization, and freezing, are reviewed in Chapter 10. Chapter 11 gives a synthesis of test results and an evaluation of each stabilization method, as well as three suggested procedures for stabilizing dredged materials in diked containment areas. Detailed conclusions regarding each phase of this study are listed at the end of each chapter, and the general conclusions which can be deduced from the overall investigation are summarized in Chapter 12.

CHAPTER 2

DEWATERING

In a recent report by the U. S. Army Engineer Waterways Experiment Station (Boyd et al, 1972), it was stated that:

> Behavioral characteristics of dredge spoil in containment areas have not been thoroughly investigated. It is apparent that most dredge spoils improve with time if drainage is provided, and at some point in time these materials can be used as foundation or building materials....Dewatering techniques must be developed to allow full utilization of the capacity of diked containment areas and/or the reuse of such areas.

Along this same line, Krizek, Karadi, and Hummel (1973) reported that the engineering behavior of most dredgings is not too different from that of a fine-grained organic soil, the properties of which can be predicted to some extent by previous testing and experience. The general impression that maintenance dredgings are soft and weak is due only in part to their inherent nature, and one very important reason for this situation is the fact that such dredgings are usually placed in low-lying swampy areas with poor drainage. If adequately drained, most dredgings can be used in a variety of circumstances as low to medium quality landfill materials. Hence, one of the principal problems faced in the disposal of polluted dredge spoil centers around the development and implementation of methods whereby it can be quickly and economically dewatered.

FIELD CONDITIONS

There are several types of dredging and disposal operations wherein the spoil is deposited in a diked containment area with large quantities of water, and, after the solids have settled, the excess water is returned to its source by means of an overflow weir or filter system. During such an operation a variety of phenomena usually occur inside the area; these include the sorting of particles according to size, the development of stratifications and fissures, the inherent softness of the landfill, desiccation, transpiration, and subsequent rewetting, and each exerts some influence on the type and effectiveness of the dewatering technique employed.

Sorting

Upon deposition of dredge spoil in a containment area, the coarse particles settle from suspension near the input end, and the fine particles that remain suspended in the water are transported closer to the outflow end before they settle. This causes a very distinct spatial variation in the particle size distribution within a containment area, thereby affecting the engineering properties of the material and the associated problems of dewatering.

Stratifications and Fissures

As a consequence of seasonal effects and/or the different types of dredge spoil deposited in a containment area, horizontal stratifications and fissures frequently occur in a landfill, thus influencing the permeability and drainage characteristics of the material. Based on a large number of permeability determinations for dredge spoil, Krizek, Jin, and Salem (1974) found that the field permeability was about two orders of magnitude higher than the laboratory permeability of homogeneous samples; this is probably due in large part to horizontal stratifications and/or fissures. Another reason for this behavior may be due to the air bubbles generated by the digestion of organic materials, thereby loosening the materials composing the landfill.

Softness

In general, the landfill within a diked containment area remains very soft for long periods of time, and the bearing capacity of the sediment may not be sufficient to support the weight of personnel or equipment. This, of course, strongly influences the means that can be taken to dewater the spoil or to implement any other stabilization method.

Desiccation

Depending on climatic conditions, the water in the pores of the sediment may evaporate and improve the strength of the material in the top few feet, thereby enabling personnel or light equipment to traverse the fill. However, capillary tension effects usually cause vertical alligator-type shrinkage cracks, and volcano-like openings may be formed to release the generated gas pressures. These effects tend to accelerate the desiccation and digestion processes and therefore improve the stability of the mass.

Transpiration

Most of the dredgings studied have been sufficiently rich in nutrients to foster a prolific growth of vegetation in a relatively short period of time. This enhances the process of dewatering due to the transpiration associated with this vegetation, and the extent of this effect is governed to a large degree by the nature of the plant and its attendant root system.

Rewetting

After any substantial rainfall, the top crust of the sediment will increase in water content and decrease in shear strength. At times, the surface of the landfill may become totally unworkable, but this effect is usually of short duration, especially if there is substantial vegetation.

The major considerations involve the development of means to remove this surface water and the effect that the associated adverse conditions, if allowed to occur, will exert on the dewatering techniques.

DEWATERING METHODS

There are a variety of dewatering methods that have been used successfully in different situations to accelerate the drainage and/or consolidation of soils. The basic idea behind each of these methods is either to reduce the drainage length or to increase the gradient causing flow, and this may be accomplished in a number of ways.

Ditching

The groundwater level in a spoil area can be lowered by a system of ditches that provide for gravity drainage of both groundwater and surface runoff; without the latter, rainfall will tend to replenish the groundwater and cause the spoil to remain soft and wet for longer periods of time. Gravity drainage and evaporation serve to reduce the water content of the dredgings and to increase their density and shear strength. Above the water table capillary tension in the material causes shrinkage, and the increased effective weight due to the loss of buoyancy enhances consolidation of the lower strata. A report by the Philadelphia District (1969) of the Corps of Engineers noted drying effects near sluices and adjacent to dikes in existing spoil areas, and, based on this observation, a system of parallel ditches at a spacing of 200 to 300 feet was suggested to drain the area; this spacing assumed the development of vertical alligator-type cracks, which serve to greatly increase lateral drainage. Because of shear strength limitations, it was further suggested that the ditch excavation be performed in 5-foot stages, but no explicit consideration was given to methods for keeping the ditches open. It is not known whether or not this proposed system of ditches was ever constructed.

Sand Drains

Vertical sand drains are often used to accelerate settlements or to stabilize foundation soils that are too weak to support a proposed loading; this is accomplished by decreasing the length of the path that pore water must flow in order to escape. Such drains are especially effective in soil deposits to wherein the horizontal permeability is higher than the vertical permeability, as appears to be the case for many landfills composed of dredge spoil; if appropriate, sand drains could also be extended into compressible subsurface soils. A theoretical study of sand drain systems for typical dredgings disposal areas was made by the Philadelphia District (1969) of the Corps of Engineers; the system involved the use of 16-inch diameter drains completely penetrating the spoil and spaced 10 feet on centers, and they required that an overlying sand blanket approximately 3 feet thick be drained by perforated pipes connected to a collector pipe laid along the dike. The results of the analysis showed that sand drains plus a surcharge will greatly accelerate consolidation of the deposits, reducing the time required for 2 to 3 feet settlement in the thicker deposits (35 feet) from over 50 years to 1 year or less. However, the problem of constructing sand drains under such adverse conditions and the economical justification for such treatment are key factors that would have to be addressed in any practical application of this method of dewatering.

Drainage Blankets

Since dredge spoil within diked containment areas is frequently placed over soft, compressible, poorly drained marsh deposits or other low-lying areas, it is not likely that very much drainage takes place through the bottom of the deposit. In such circumstances horizontal sand blankets appear to have potential as a method for draining both the dredge spoil and the subsurface soils, thereby accelerating their consolidation. The sand blanket would have to be placed in the disposal site prior to the deposition of any dredgings, and proper consideration would have to be taken to assure that it satisfied applicable filter requirements and that it was adequately drained. Although probably feasible from a technical point of view, this method of dewatering may not be economically justified in most situation.

Preloading

The placement of a dead load on the surface of soft foundation soils for the purpose of developing settlements and increasing their shear strength prior to construction is known as preloading. In order to take advantage of the additional shear strength that develops as consolidation progresses, the optimum loading rate must be used; this is the maximum rate at which the load can be placed without causing a stability failure. The essential problem associated with the use of this method is to find techniques for handling, depositing, and consolidating the dredgings to densities and shear strengths of sufficient magnitude to allow the preload to be applied.

Other Methods

Various other dewatering techniques, such as vacuum drainage, electroosmosis, evaporation, and transpiration, are available, and these will be discussed in subsequent chapters. The first two techniques may be useful for rapid dewatering of dredgings in "processing areas" to a water content near optimum prior to using them to construct a fill by more-or-less conventional methods; however, neither method appears feasible for dewatering an in-situ landfill composed of dredgings. Evaporation seems to offer good potential for the economical dewatering of dredge spoil, provided appropriate "conditioning" of the spoil is undertaken. Although the potential for dewatering by transpiration appears significant, especially within several feet of the surface, quantitative data are lacking. In addition, certain modifications to the foregoing methods offer the promise of success; these include the use of cardboard wicks, pervious plastic drains, pervious dikes, sandfill weirs, etc., but an appraisal of their success awaits further experience. One other means for enhancing the ability to dewater a site involves a periodic repositioning of inflow and outflow points for a given disposal site, thereby improving the gross homogeneity of the site and increasing the permeability in certain regions.

IMPROVEMENTS IN ENGINEERING CHARACTERISTICS

It is well known that the engineering characteristics of a soil depend in large part on its water content. In general, as the water content decreases, the shear strength and density increase and the compressibility decreases, provided the soil structures are essentially the same. For this reason dewatering offers one of the most effective techniques for improving the engineering properties of dredge spoil. In addition, the weathering, degradation, and digestion action may increase with dewatering. Krizek, Karadi, and Hummel (1973) have shown from field and laboratory test data that there is a general tendency for the low water content sediments in the upper and lower parts of a dredgings disposal area to have higher strength, lower compressibility, and lower permeability than those materials in the middle of the landfill. The lower water contents of the upper and lower parts of the profile are probably due, respectively, to desiccation effects and consolidation resulting from bottom drainage. Hence, with adequate dewatering the engineering characteristics of the material in the middle part of the profile can equal those of the spoil at the top and bottom. As indicated in the foregoing discussion, a certain degree of stability is necessary before many of these dewatering techniques can be applied effectively to a landfill composed of dredge spoil; one of the possible ways to obtain this stability lies in the use of various additives which may be combined with the dredgings prior to their deposition in the containment area.

CHAPTER 3

STABILIZATION METHODS

The use of polluted maintenance dredgings as landfill materials presents two major problems; the first is a soils engineering problem that is concerned with the methods whereby the thin slurry can be converted into landfill material with acceptable engineering properties, and the second is an environmental engineering problem that relates to the possible pollution of the surrounding area and the groundwater. Usually the landfilling process is the final step of a dredging and disposal cycle wherein polluted sediments are dredged from the bottoms of harbors and navigation channels and deposited into diked containment areas. In the particular case of a hopper dredge operation, for example, the material is pumped into the disposal area through a discharge pipe; most of the solid constituents settle from suspension and are retained within the diked enclosure, whereas much of the water, together with some disolved and suspended solids, either returns to its source over a weir or through a filtering system or seeps through the sediment into the underlying groundwater. In the process of constructing such a landfill, certain other effects, such as precipitation, evaporation, transpiration through plant growth, and/or stratification due to seasonal variations, may take place. In order to establish a background within which to seek possible solutions for the problem of stabilizing these soft sediments of dredge spoil, a literature review was undertaken and the results are reported in this chapter. A number of existing methods for the stabilization of dredging materials are discussed and evaluated, but special emphasis is given to chemical stabilization; in addition, various field and laboratory treatment processes for dredge spoil are considered. Since most of the dredging materials encountered in this investigation may be classified as organic clayey silts, the principal stabilization methods reviewed herein are those which are effective for these types of soils.

CHEMICAL STABILIZATION

There are times in a dredging and disposal process when chemicals could be effectively added to the dredge spoil and mixed thoroughly with virtually no alteration in the normal cycle. If these chemicals could substantially improve the engineering characteristics of the resulting sediments, the end product may be economically justified. During the past few decades a large number of chemical additives have been developed to stabilize soft soil sediments, but it has been difficult to clearly identify the benefits and limitations of each. In general, each additive is most effective for certain types of soils and under certain conditions of usage, and it is important to classify and evaluate their applicability and economy in this light.

Lime

To date the most detailed and well-documented studies of effective stabilizing agents have dealt with lime-clay systems. The reaction of lime with clayey materials in the presence of moisture is two-fold. First, there is a base exchange in which the calcium cations from the lime displace the sodium, hydrogen, and other cations of the soil;

almost immediately an agglomerating action occurs, and the fine clay particles accrete into coarser silt and fine sand sizes, thereby yielding more friable particles. Second, after compaction and curing, there develops a definite "cementing" or hardening action in which the lime reacts chemically with the available silica and some alumina in the raw soil (or with pozzolanic additives, such as fly ash, volcanic ash, or expanded shale fines) to form complex calcium silicates and aluminates. These reaction products constitute an insoluble binder for the monolithic-like soil matrix. In general, the addition of lime to a soil causes the following desirable modifications in its engineering properties.

1. There is a decrease in the plasticity of the soil, and some soils may actually become non-plastic with the amount of stabilizer normally used. Marks and Haliburton (1970) explain this phenomenon by suggesting that monovalent diffused ions in the double layer become dissociated as divalent calcium ions are released by addition of lime, thereby causing some compression of the double layer, an associated flocculation of the clay particles, and a reduction in plasticity.

2. The strength increases due to pozzolanic reactions of two types; first, there is a reaction of calcium ions with aluminum hydroxyl groups to form tetracalcium aluminatic hydrates that produce quick, low-strength, cementation bonds, and second, there is a reaction of calcium with silica to form complex calcium silicates and aluminates that are responsible for the long term gain in strength or the so-called cementing action.

3. The soil is agglomerated, thereby decreasing the soil binder content substantially and accelerating the disintegration of clay clods during mixing; as a result the soil becomes friable and can be easily worked.

4. The shrink-swell potential is reduced markedly; in addition, lime enhances the desiccation of wet soil, thus accelerating the time at which it can be effective compacted.

5. The lime stabilized layer forms a water-resistant barrier by impeding the penetration of gravity water from above and capillary moisture from below; hence, the layer becomes a firm "working table" that sheds rain water readily and remains stable.

Drake and Haliburton (1972) studied temperature accelerated curing of two Oklahoma cohesive soils (a medium plastic clay and a highly plastic clay) modified and stabilized with lime and salt-lime additives. After determining the temperature and time required to obtain a strength equivalent to that obtained by curing in a moist room for 28 days at 80°F and 100% humidity, they compared the unconfined compressive strength results and DTA data and concluded that:

1. An accelerated curing process can be used to achieve a 28-day unconfined compressive strength equal to that obtained for samples cured in a moist room; when both soils were subjected to a salt-lime modification and stabilization treatment, 30 hours of curing at 105°F produced an equivalent 28-day strength.

2. For the lime content used, the reduction in the curing time from 72 hours to 30 hours caused by the addition of salt confirms the catalytic effect of NaCl on lime-soil reactions.

Alexander, Smith, and Sherman (1972) investigated the relative stabilizing effects of two hydrated limes and three quicklimes from various commercial producers. The effects of variation in lime gradation and calcium hydroxide content on the unconfined compressive strengths of three different soils were compared, and they concluded that:

1. When compared on an equal-percentage-by-weight basis, quicklime is generally more effective than hydrated lime for improving the compressive strength of soils; this is due primarily to the greater calcium hydroxide potential of quicklime (the quicklimes included in this study had an equivalence of approximately 50 percent more calcium hydroxide than the hydrated limes of the same weight). When compared on the basis of equivalent $Ca(OH)_2$ content, all forms of quicklime studied equaled or exceeded the effectiveness of the hydrated limes in improving the compressive strength of soils.

2. At lime contents above 2 percent, higher compressive strengths are obtained with the coarser quicklime products than with those ground excessively fine; this is apparently due to the effect that the fine limes have on reducing the compactibility of the treated soil. The resulting lower densities and strengths of test specimens offset the benefits that would otherwise be expected from use of the fine limes.

3. A fineness of hydrated lime of more than 75 percent passing the No. 200 sieve does not appear to increase its effectiveness in soil stabilization.

4. A loose-curing period for soils treated with quicklime is required to prevent expansion and pop-outs caused by hydration of the lime; according to laboratory tests, a 24-hour period appears satisfactory.

Concurrent with investigating the lime reactivity (ability of a soil to react with lime to achieve a strength increase) of Illinois soils, Thompson (1966) studied the lime-soil reactions and the physico-chemical properties of soils and attributed the improvements in the engineering character of lime-soil mixtures to the following four basic reactions:

1. Cation Exchange:-The general order of replaceability of the common cations associated with soils is given by the lytropic series, $Na^+ < K^+ < Ca^{++} < Mg^{++}$; any cation will tend to replace the cations to the left of it, and monovalent cations are usually replaceable by multi-valent cations. The addition of lime to a soil supplies an excess of Ca^{++} and cation exchange will occur with Ca^{++} replacing dissimilar cations from the exchange complex of the soil. In some cases the exchange complex is practically Ca^{++} saturated before the lime addition and cation exchange does not occur or is minimized.

2. Flocculation and Agglomeration:-The addition of lime to a fine-grained soil causes flocculation and agglomeration of the clay fraction; these reactions result in an apparent change in the texture of the soil, the clay particle "clumping" together to form larger sized "aggregates". The flocculation and agglomeration are affected by the increased electrolyte content of the pore water and the associated ion exchange by the clay to the calcium form.

3. Lime Carbonation:-Lime reacts with carbon dioxide to form relatively weak cementing agents, which may be either calcium carbonate or magnesium carbonate, depending on the type of lime used. Eades, Nichols, and Grim (1962) reported field conditions where 2.5% of $CaCO_3$ formed because of the carbonation reaction.

4. Pozzolanic Reaction:-The pozzolanic reaction in lime-soil stabilization is a reaction between soil silica and/or alumina and lime to form various types of cementing agents, which are generally regarded as the major source of the strength increases in lime-soil mixtures. Possible sources of silica and alumina in typical soils include clay minerals, quartz, feldspars, micas, and other similar silicate or aluminosilicate minerals.

Based on the results of the lime reactivity investigation on Illinois soils, the following conclusions were drawn:

1. The lime reactivity of a soil is determined by certain natural soil properties.

2. The liquid limit, plasticity index, group index, and clay content ($< 2\mu$) of a soil do not significantly influence its lime reactivity.

3. For the soils included in the investigation, the average clay content (montmorillonite plus mixed-layer) was significantly greater for the group of soils displaying the highest lime reactivity.

4. Cation exchange capacity, total exchangeable bases, and exchangeable bases (Ca, Mg, Na, K) are not significantly correlated with lime reactivity.

5. Higher percentages of base saturation increased the lime reactivity of a soil.

6. Soils with a high pH showed better lime reactivity than soils with a low pH; as the pH increases, less H^+ are absorbed (which means a higher percentage of base saturation).

7. For the soils tested it was observed that high Ca/Mg rations in the composition of the soils were related to good lime reactivity. As soil development progresses, exchangeable Ca^{++} is leached and Mg^{++} remains. The leaching of Ca^{++} will leave positions in the exchange complex that are assumed by the H^+ ions, thereby decreasing the percentage of base saturation; in other words, a high Ca/Mg ratio correlates with a high percentage of base saturation.

8. Poorly drained soils display higher lime reactivities than well drained soils.

9. All calcareous soils displayed higher lime reactivity than non-calcareous ones; since the calcareous soils are parent materials and have not been subjected to extensive weathering, soil minerals with low weathering resistance are still present and serve as excellent silica and alumina sources for pozzolanic reaction.

Based on a study by Arman and Munfakh (1972) to evaluate the potential for using lime to improve the engineering characteristics of organic soils found in Louisiana, the following conclusions were advanced:

1. The presence of organic matter in soil does not preclude the occurrence of pozzolanic reaction.

2. Changes in the pH of soil-lime mixtures (containing 20 percent organic matter) showed that increased levels of lime treatment were able to neutralize the acidity of the organic matter in the soil and initiate the soil-lime reaction; the addition of less than 2 percent lime is sufficient to satisfy the base exchange capacity of the organic matter in the soil (based on the assumption that a pH of 7 indicates satisfaction of the exchange capacity).

Chlorides

As discussed by Gow, Davidson, and Sheeler (1960), the mechanism of soil stabilization with chlorides can be attributed to seven effects.

1. Lubrication:-As a consequence of the unctuous nature of chloride solutions, compacted densities are only about 1 to 7 percent greater than those of untreated soils; these increases in density may logically be expected to increase the strength and reduce the rate of moisture loss. Although this effect is less pronounced with sodium chloride than with calcium chloride, the difference may be negligible, since sodium chloride contributes to dispersion of the fines, thus preventing localized concentrations and soft spots in the mass.

2. Flocculation:-The presence of certain amounts of sodium or calcium ions in the mix will flocculate the fines into silt-sized particles; this amounts to changing the grain size distribution and may have the effect of reducing the plasticity index. Other concentrations of ions will cause electrical imbalances, which will tend to disperse the clay. Crystallization of the salt or leaching by rainfall will change the concentration of ions, thus permitting dispersion of the clay and consequent plugging of voids.

3. Moisture retention:-Because of the deliquescence of calcium chloride and the hydroscopicity of sodium chloride, the rate of evaporation of soil moisture will be reduced; as a result, the cohesiveness of the soil will be retained and the finer fraction will function as desired, rather than being lost as dust.

4. Solubility of coarse particles:-This effect is mentioned as a possible means of cementation within the mix and is based on the solubility of limestone and dolomite in chloride solutions, thereby resulting in the precipitation of cementious carbonates.

5. Freezing point depression:-By lowering the freezing point of the mixture, resistance to temperature effects is obtained; for complete freezing temperatures must be -59.8°F with calcium chloride treatment or -6°F with sodium chloride treatment.

6. Surface tension:-The increase in this property due to the presence of chlorides results in strengthening the water film bonds between soil grains, thus increasing the apparent cohesion. With evaporation the chloride concentration increases and causes a further increase in surface tension; the degree of increase may be such that increased densities will result.

7. Crystallization:-This effect is present only with sodium chloride and may compensate for the reduced effectiveness of salt in altering other properties; the advantages obtained from the formation of salt crystals include retarded evaporation and shrinkage due to the fact that the crystals plug the voids.

Alkalis and Inorganic Acids

Ingles (1970) investigated the mechanisms of clay stabilization with inorganic acids and alkalis. A series of mono- and di-valent cation hydroxides and certain strong acids were allowed to react with a two- and a three-layer clay mineral (Kaolinite and montmorillonite) under conditions simulating those for normal soil stabilization in field practice (that is, mixed, remoulded, and moist-cured at a water content and density approximating optimum compaction conditions). Changes in strength and volume were correlated with chemical and mineralogical changes in order to identify those bonding mechanisms which contribute to inorganic soil stabilization. For an additive level of 10% by weight (dry clay basis) it was shown that several distinct stabilization mechanisms exist. One major mechanism is the surface coating of fabric units, and another is the reinforcement of the soil by product formation in crevices, angularities, pore constrictions, and similar defects. These postulates were concordant with the chemical analysis, X-ray analysis, electron micrographs, and mechanical tests. Described in the following paragraphs are the observed reactions with kaolinite and montmorillonite.

1. Reactions with kaolinite

(a) $Ba(OH)_2 \cdot 8H_2O$ and $Ca(OH)_2$

With the divalent alkali treatment virtually no silica could be extracted at any time; this is in accord with the very insoluble nature of the calcium and barium silicates and aluminates. The presence of calcium and barium ions as hydroxide in the extracts implies that they migrate to and react at the silica or alumina rich surfaces (that is, the clay) to coat it with an insoluble product. The much more marked reduction of calcium ions, as opposed to barium ions, in the sample extracts is thought to reflect the naturally better mixing of the former due to the very fine grain size of calcium hydroxide. Indications are that the added hydroxide also becomes rapidly coated with some water-insoluble, acid-soluble product; this could result from the entrapment of hydroxide grains (sealed off by the intergrown silicate coat) within a skeleton of coated clay grains. The growth of occasional crystals of metal silicate hydrates is often deletrious to strength development, since the hydrated crystalline phase will withdraw water from the interstitial solution and thus stop further reaction.

(b) $LiOH \cdot H_2O$

The lack of any strength gain by use of this treatment was accompanied by a significant volumetric expansion and evidence of a very limited reaction.

(c) NaOH and $KOH \cdot \frac{1}{2}H_2O$

Both treatments resulted in substantial strength gains after an initial induction period of about 7 to 10 days, during which time the strength was less than that of the untreated clay. This behavior arises from the initial dissolution of the clay mineral lattice with subsequent crystallization of alumina in the environment of a high Al/Si ratio in the liquid phase. Unlike KOH, NaOH causes some swelling of the specimens, without which strength gains would presumably have been even higher. Grain coatings were visible to the unaided eye. It follows from the open texture (large voids were visible between granules) that strength grains are due to the fabric unit coatings. The volumetric expansion with NaOH is ascribed to the formation of water-insoluble sodium alumino-silicate. However, since strength gains do not correlate with the rapid removal of cations as crystallized complexes; these gains are attributed to the nordstrandites and not the alumino-silicates. In the case of the KOH treated specimens, small nodular efflorescences were observed after long periods of curing; upon separation these proved to be pure gibbsite. An important feature of all the monovalent alkali-kaolin specimens was the high water content at 100°C; this suggests an almost immediate dissolution of the clay and, in particular, an attack on the octahedral layer with the liberation of simple hydrates or even water.

(d) NH_4OH

As expected, this treatment sharply reduced the strength; this is a consequence of its inability to form insoluble salts and its weakening effect on interlayer attractions.

(e) HF

Despite its vigorous attack on a clay mineral, which was expected to yield only insoluble reaction products, no strength gain or loss was observed. Although some volumetric expansion occurred, this would not account for the lack of significant strength gain. The pH increased to approach a neutral condition, and evidently -OH groups were liberated by HF attack on the clay lattice. Thus, the only tenable explanation for the invariant strength of this system appears to lie in the counterbalancing effects of a weakened aluminous phase and a reinforced siliceous phase on the surface of the clay fabric units (the added HF is insufficient to cause a total reaction with the clay).

(f) H_3PO_4

Although the formation of insoluble calcium phosphate was expected from this clay (this is not contradicted by the low level of the soluble calcium), it is, if formed, evidently insufficient to cause any strength gain. There is little or no evidence of any appreciable reaction with the clay.

(g) CH_3COOH

Substantial strength losses were noted; this was expected because of the known effect of acetic acid in reducing interlayer attractive forces in the clay and thereby facilitating shear.

2. Reactions with montmorillonite

(a) $Ba(OH)_2 \cdot 8H_2O$

The chemical data indicate that the initial strength gain, which is achieved within 24 hours, is associated with the displacement of sodium by barium from the exchange complex and/or the precipitation of barium by the carbonate ion associated with the clay. The very low values for water-extractable barium and the increase in extractable silica afford clear evidence of the formation of an insoluble coating on the reactant hydroxide. Since barium silicate and barium carbonate are both acid soluble, the high concentration of OH^- indicates that the reaction is largely frozen by a very thin initial coat formation. The lowered exchange capacity provides further confirmation of this hypothesis, and the slight volumetric increase with time is ascribed to slow crystallization of the (presumed) gelatinous silicate.

(b) $Ca(OH)_2$

An initial strength gain, comparable to that from the $Ba(OH)_2$ treatment, was observed, but, unlike the latter, the strength increased substantially with time for approximately 1 month. The major strength increases after a month of curing were accompanied by sharp volumetric decreases and a diminution of apparent water contents. Since the volumetric decreases appear to arise from the formation of tobermorite and/or anorthite, it is inferred that the major strength gains recorded at one month by the calcium hydroxide treated montmorillonite are directly linked to the volumetric contraction associated with the low-hydration crystallization of the (mono) calcium silicate gel.

(c) $LiOH \cdot H_2O$

In sharp contrast to the $Ca(OH)_2$ treatment of montmorillonite, LiOH treatment causes, not only a substantial strength gain, but also a volumetric expansion upon aging. Sodium is liberated from the clay exchange complex, whereas the pH and OH^- content remain high; this implies an initial cation exchange (which, however, does not lead to a strength gain, since a monovalent ion is replaced by a monovalent ion) followed by a precipitation of insoluble silicate coatings on the reactants. Lithium metasilicate was positively identified, thereby suggesting an abundance of soluble silica and a deposition of the silicate preferentially on the surface of untreated hydroxide. Electron micrographs confirmed the very limited nature of any attack on the clay mineral. Major strength gains continued after the expansion had almost ceased, and strength in this system therefore appears to be attributable solely to lattice penetration by the lithium ion. Even the strongest LiOH treated specimens are unstable to water immersion, thus confirming the hypothesis that the clay fabric units are essentially unprotected by any coating (lithium silicate is cold water insoluble). It is therefore necessary to conclude that these strength gains are attributable to enhanced electro-static bonding on the shear planes of the clay.

(d) $KOH \cdot \frac{1}{2}H_2O$ and NaOH

Both alkalis cause a similar substantial and permanent loss of strength, which is attributed to micro-failures along shear planes across which the initially weak electro-static bonds have been instantly destroyed by the vigorous surface attack of the alkali hydroxides and the formation of a soft (water miscible) surface gel; this is the reverse of the LiOH effect.

(e) NH_4OH

Some short-term tests with ammonia-treated montmorillonite resulted in very low strengths; this was expected because of its high expansion potential and the fact that ammonium does not form insoluble salts.

(f) HF

Strength increased steadily to a substantial level; this was clearly attributable to the formation of fabric unit coats of insoluble fluosilicate. The high base exchange capacity of the montmorillonite was effectively destroyed by this acid treatment, and this is a major point of difference from the alkaline treatments.

(g) H_3PO_4

This acid is capable of forming insoluble salts (for example, calcium phosphate), and it might therefore be expected to strengthen some clays. In the present instance, however, no strength gain was recorded, and this is attributed to the inability of the sodium montmorillonite to form any insoluble reaction product (the major water-soluble product after extended curing was sodium phosphate).

(h) CH_3COOH

This is a weak acid that is unable to form insoluble products, and it was therefore not expected to enhance strength. This was confirmed over a 3-month curing period, and substantial strength losses were noted.

It is evident from the foregoing results that the ability to resist water enhanced the strength of both kaolinite and montmorillinite, and this quality is obtained only if a water-insoluble product appears as a result of the degradation of the clay. The degradation of the clay to form water-miscible products leads to a diminution of strength at a given level of compaction. Nevertheless, not all systems which deposit water-insoluble reaction products lead to equivalent strength gains. One possible source of differential behavior arises from the density of the insoluble product; if this occasions a volumetric increase or decrease in the system, anticipated strength gains might be changed in a reciprocal manner.

Since silica is the only constituent that is found in large quantities in all clay minerals, the formation of insoluble silicon compounds characterizes those stabilizers with the widest spectrum of applicability for soils; this explains the wide spread use of lime and cement as soil stabilizers. For kaolinite clays (high aluminum content) an insoluble aluminate system is possible, and this is exemplified in the beneficial effects of the alkali hydroxides. For stabilization systems which depend on clay degradation, two regions may be distinguished:

$pH > 12$ Region of cationic stabilization

$pH < 2$ Region of anionic stabilization.

For intermediate pH ranges any stabilization must be achieved by the matrix formation of a third phase, in which the clay plays a role (mechanically) that is essentially similar to a weak filler material, although minor strength effects may be observed.

Organic Chemicals

The amount of moisture in a soil and its association with individual soil particles may be influenced by small additions of organic cationic compounds. When organic cations are added to a soil, the negative surface charge of clay particles is balanced by the cationic end of the chemical; accordingly, the clay tends to flocculate and has less ability to take up water. In addition, the particle surfaces are partially coated with a thin film of a dilute solution of the organic cationic compound, which exposes its hydrophobic end; thus, the soil particles are essentially waterproofed. Excessive additions of organic cations (above the optimum percentage for the soil) will more completely coat soil particles and destroy the bonding action of the water; this, in part, explains why strength is reduced if organic cations are added above the optimum amount.

Because of the strong electric field associated with inorganic cations, water dipoles are oriented with respect to the cation and the clay particle. Since the affinity for water in this system is relatively great, additional water can enter and cause disorganization of the oriented dipoles. Organic cations, however, set up a weaker electric field, thus inducing less orientation of water dipoles; the affinity for water is weak, and additional water is not pulled into the system. Organic cations also reduce the surface tension in a soil-water mixture. This reduction has two pronounced effects on the soil; first, the cohesion is reduced and, second, the surface free energy is reduced. The lowered cohesion results in a decrease in both strength and plasticity. As a consequence of thermodynamic considerations, the decrease in the surface free energy retards the absorption of excess water, thereby resulting in a waterproofing condition. In addition, organic cations are adsorbed between layers of the expendable lattice minerals of the montmorillonite group, and they retard changes in the thickness of water films between these layers, thereby reducing the shrink-swell potential of the expandable lattice minerals. In general, larger organic cations exert a greater effect in reducing the water absorbing capacity of the treated soil.

As summarized in Table 3-1, Chang and Anderson (1968) investigated the effect of 15 substituted benzene ring compounds on the flocculation of < 2μ Gila clay (mostly well-crystallized montmorillonite and interstratified montmorillonite and vermiculite plus about 25% illite and 10% allophane) which was subjected to various pretreatments with varied exchangeable sodium percentages; in general, they found that the optimum percentages for flocculation were in the following order: calcareous clays > non-calcareous, calcium-saturated clays > non-calcareous

Table 3-1. Chemical Compounds and Pertinent Properties (After Chang and Anderson, 1968)

Compound	Substituted Group	Pairs of Unshared Electrons	Initial pH and Conductivity 20 millimoles/liter		Molecular Weight	Grade
			pH	Ec x 10^6 ••		
phenol	1-OH	2	5.8	<10	94	Reagent
o-nitrophenol	1-OH, 1-NO_2	7	5.2	<10	139	Eastman
p-nitrophenol	1-OH, 1-NO_2	7	4.8	<10	139	Eastman
trinitrophenol	1-OH, 3-NO_2	17	2.1	440	229	Eastman
p-phenylene-diamine	2-NO_2	2	8.6	<10	108	Eastman
p-benezoquinone	2-O	4	4.7	<10	108	Eastman
hydroquinone	2-OH	4	5.4	<10	110	Purified
quinhydrone	2-OH, 2-O	4	5.2	<10	218	Reagent
pyrogallol	3-OH	6	5.4	<10	126	Eastman
gallic acid	3-OH, COOH	10	3.2	280	170	Reagent
tannin (m-digallic acid)	5-OH, COOH	18	3.7	100	322•••	NF
resorcinol	2-OH	4	5.8	<10	110	Reagent
EDTA (acid form)	•	16	3.2	500	292	Eastman
sorbitol	•	12	6.0	<10	182	Eastman
d-glucurono-lactone	•	12	4.6	<10	176	Eastman

• Nonaromatic compounds

•• Electrical conductivity in mhos x 10^6

••• Approximate

sodium-saturated clays. However, the results of removing organic matter from the clays were not statistically significant, and they do not support the hypothesis that naturally occurring organic matter serves as preferred points of attachment for organic compounds. The flocculation effectiveness of the added organic compounds on the calcareous clay increased as the pH of the resulting systems dropped to about 6; this is attributed to the formation of soluble calcium salts and to the resulting exchange of calcium for sodium.

The Ca-trinitrophenol, calcium clay system flocculated almost instantly, and the resulting flocs settled into a dense mass at the bottom of the hydrometer jar. In contrast, sodium clay treated with Na-trinitrophenol appeared to form as stable a suspension as the untreated sodium clay. Each of these remained suspended for about a week. Flocculation occurred more rapidly in the Na-clay, Ca-trinitrophenol system than in the Ca-clay, Na-trinitrophenol system; this can be explained by the fact that the former contained the larger concentration of Ca ions. These results indicate that the effectiveness of trinitrophenol does not depend entirely on a low pH, but they also show that it is ineffective in systems wherein Na is the only cation. A comparison with an equivalent Ca-clay, $CaCl_2$ system showed that the Ca-trinitrophenol was much more effective in producing rapid and complete flocculation; hence, its effect was not simply dependent on the concentration of soluble Ca ions.

Partial information about the mechanisms of reaction is supplied by the X-rady diffraction data. It was found that, although interlayer absorption of most of the effective flocculating agents has been shown to occur, this work shows that neutral sodium-trinitrophenol suspensions do not flocculate, even though interlayer absorption occurs. This indicates that the interlayer absorption is primarily in existing clay micelles and that it does not involve an increase in the size of existing micelles by the addition of clay layers and interspersed organic molecules. Two mechanisms have been postulated to account for the observed flocculation of clays by organic compounds:

1. Clay particles are linked together by substituted aromatic compounds that act as dipoles with cation linkage at the negative ends and with cationic adsorption of the positive end; such linkage could also be accomplished by coordination complexes of the organic compounds.
2. Clay particles are linked together by chelating agents (such as EDTA) which are capable of forming stable bonds with aluminum and iron at the edges of clay particles.

The flocculating ability of the compounds studied varies with both the nature and the position of the functional groups. The effectiveness of organic compounds appears to depend in part on the number of active groups (such as NO_2^+ and $O^=$) and on the number of unshared electrons. Reactive groups of benzene ring compounds appear more effective in the meta than in the ortho or para positions.

Michaels (1954) studied the aggregating capacity of a polymer whose degree of electrolytic character can be varied over a wide range. The compound selected was the product obtained by the aqueous phase, redox-catalyzed polymerization of acrylamide. This water-soluble polymer was hydrolyzed to controlled degrees with sodium hydroxide to produce compounds containing varying proportions of the amide and carboxylate groups. Samples of two natural soils (Virginia sandy clay and New Hampshire silt) were used in the investigation. The results showed that the aggregation of the soil upon addition of the polymer was a function of soil type, degree of hydrolysis, concentration of polymer, and molecular weight of polymer. Several important trends are:

1. In most cases studied the higher aggregating capacity of the added polymers favors the higher molecular weight species, all other factors being held constant.

2. For both soils tested the aggregating capacity of polyacrylamide reached an optimum at a degree of hydrolysis in the neighborhood of 28% to 35%. At the lower levels of polymer concentration (0.01% to 0.04%), there also appeared to be a slight aggregating ability at a low (about 10%)degree of hydrolysis. In most cases with these two soils the unhydrolyzed polyacrylamide appeared to be more effective than the completely hydrolyzed compound.

3. The effect of polymer concentration on flocculation had no consistent relation with the degree of hydrolysis.

These observations can be used to formulate a hypothesis for the mechanism by which water-soluble polymers can cause aggregation. Basically, for a polymer to cause flocculation by reducing the electrokinetic potential of a solid surface, it must possess an ionic character opposite to that of the solid surface. In most cases soils carry a negative charge in an essentially neutral aqueous environment and cationic polyelectrolytes would be expected to be active flocculants for such systems. Naturally, a cationic polyelectrolyte molecule may not only cause flocculation by reducing the electro-kinetic potential, but it may take an active part in the flocculating process by being adsorbed on more than one particle. On the other hand, anionic polyelectrolytes should not be responsible for flocculation by the mere alteration of electro-kinetic potential. Furthermore, the anionic groups associated with these polymers can not easily be visualized as undergoing strong adsorption on negatively charged surfaces.

There are a number of water-soluble polymers without electrolyte characteristics (such as polysaccharides, etc.), and these act as powerful flocculants. These compounds are characterized as predominantly linear in structure, and they contain a rather high molecular concentration of hydroxyl groups. Due to the occurrence of hydrogen bonding with consequent cross linking and gelation of the polymer, the reaction may take place between the polysaccharides and the hydrated surfaces of minerals. Since these polymers are fairly large in size, it is possible that the process of flocculation involves adsorption via hydrogen bonding and "bridging" of particles via polysaccharide chains.

However, polyacrylamides are relatively poor aggregants; this may be due to the differences in the molecular configuration of polysaccharides and polyacrylamide. The linear polysaccharides, because of the rigidity of their inter-ring linkages, exist in solution as fairly stiff, extended rods, whereas the polyacrylamides are flexible chains which can fold, kink, or coil in solution. By introducing ionized groups at intervals into the polyacrylamide chain the electrostatic repulsive forces between adjacent charged groups may elongate the polymer structure. Consequently, the aggregating ability is increased up to a point at which maximum chain extension is achieved without marked electro-static interference with polymer adsorption, and this is followed by a gradual decrease in this capacity as the polymer is rendered more electro-negative.

The reduction in aggregating ability at a low degree of hydrolysis can be explained by the fact that unhydrolyzed polyacrylamide is not completely non-ionic and contains a small amount of cationic "amidinium" group ($-CONH_3^+$). This slight cationic characteristic favors adsorption on negative surfaces, as well as a slight degree of chain extension in

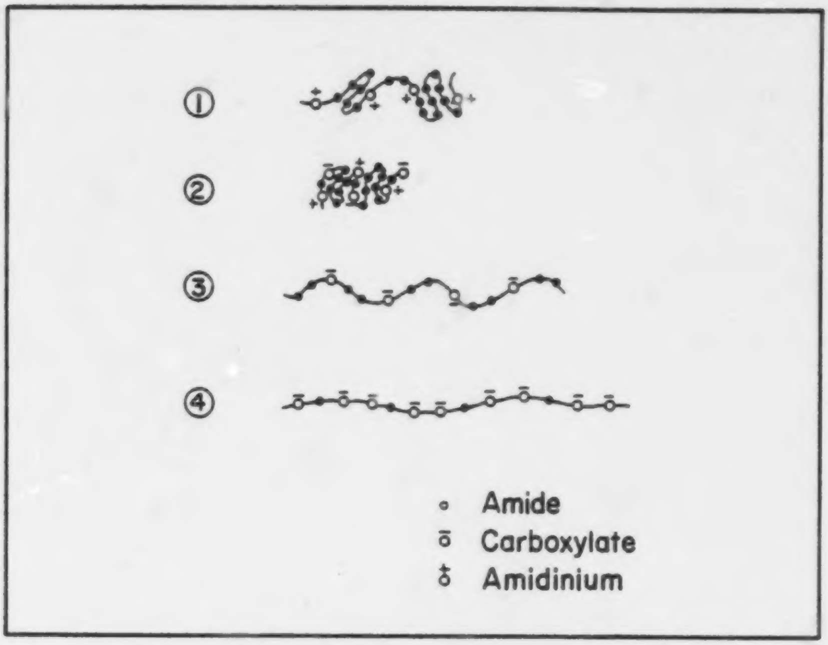


Figure 3-1. Effect of Hydrolysis on Polyacrylamide Characteristics (after Michaels, 1954)

solution. A slight hydrolysis with the formation of isolated anionic carboylate groups renders the polymer electro-statically neutral (a condition of maximum coiling and minimum aggregating ability). These changes in the characteristics of polyacrylamide on hydrolysis are illustrated in Figure 3-1. Evidently, for an active aggregant there is an optimum polymer concentration for maximum flocculation. If excess polymer is available in solution, all available adsorptive positions on the suspended particle surfaces can be satisfied by the adsorption of individual polymers and bridging effects will be minimized. Also, the adsorbed polymer is strongly hydrophilic and charged, thus resulting in stabilization of the dispersion.

In summary, the aggregating action of non-ionic or anionic water-soluble polymers is caused by the adsorption of hydroxyl or amide groups on the solid surfaces, each polymer chain being adsorbed on and bridging between more than one solid particle. The presence of ionic groups in these compounds is necessary only for flexible-chain systems, and these groups serve to extend the polymer chains, prevent intramolecular polar group associations, and enhance interparticle bridging.

Kijne (1967) investigated the influence of two soil conditioners (Krilium and polyvinyl alcohol) on the soil-water diffusivity of two differently textured soils (a clay-loam, known as Urrbrae red-brown earth, and a loamy sand, known as solodized solonetz). Flow into horizontal soil columns at 2 mbar suction was studied with two permeating liquids (a 0.01 N $CaSO_4$ solution in distilled water and n-heptane). It was found that the treatment of a clay loam with these soil conditioners caused a 1.5 to 3.0-fold increase in the soil-water diffusivity over the entire range of volumetric water contents, and, when expressed as a function of soil-water potential, the soil-water diffusivity increased more than 10-fold at the lower soil-water potentials. The same treatment had less effect on the soil-water diffusivity of the loamy sand. For both soils the rate of movement of the wetting front increased as a result of the treatments, and the infiltration rate decreased in the order of PVA treated, Krilium treated, and untreated, the difference being significant in the Urrbrae soil. It appears that stabilization of soil aggregates by the introduction of PVA may be due to the lining of soil pores. As indicated by the higher contact angle for the Krilium treated solodized solonetz samples, Krilium treatment may be rendered slightly more hydrophobic in behavior. Of the two soil conditions studied, PVA, due to its mode of attachment, is the more effective in influencing the water conducting properties of these soils.

VACUUM DEWATERING

Atmospheric pressure has been used to preload and thereby dewater and consolidate soft soil deposits; this is accomplished by applying a partial vacuum within a system of sand-filled wells or to an underlying sand blanket while maintaining the surface virtually impermeable to air. In addition to the expense associated with applying the vacuum, one of the main problems with this method lies in achieving the surface seal to prevent loss of vacuum, thereby rendering the preload (atmospheric pressure) ineffective. This method has been used largely in the dewatering of construction sites for excavation. Krizek, Karadi, and Hummel (1973) conducted an experimental laboratory program to investigate the drainage characteristics of various dredging materials subjected to a partial vacuum, and they concluded that:

1. Vacuum drainage removes water from dredgings much faster than gravity drainage alone, and it allows greater amounts of water to be extracted in a given period of time.

2. The maximum effects of vacuum on the drainage response is achieved during the initial stages; less significant effects are observed over longer periods of time.

3. Different dredgings drain at different rates and are affected to different degress by vacuum drainage.

4. The drainage characteristics of a given material depend on the nature of the solids and the fluids, as well as the water content at the time of drainage.

5. In general, the shear strengths of the vacuum drained samples are several times those of the gravity drained samples.

6. If dewatering by use of a partial vacuum is considered for a particular dredgings disposal site, appropriate drainage test should be conducted on the particular material in question to determine the specific effects of vacuum compared to gravity alone, since previous results indicated that significant differences may be observed for different materials.

ELECTRO-OSMOSIS

Although different theories have been advanced to describe the process of electro-osmosis, the following practical relationship is useful:

$$q_e = k_e \, i_e \, A \tag{3-1}$$

where q_e is the electro-osmotic flow rate, k_e is the coefficient of electro-osmotic permeability, i_e is the electrical gradient, and A is the cross-sectional area. L. Casagrande (1949) showed that, from a practical point of view, the electro-osmotic transport of water may be assumed to be constant for all types of soils, and the magnitude of the coefficient of electro-osmotic permeability was found to be about 5×10^{-5} cm^2/sec-volt. The efficiency and economy of stabilization by electro-osmosis depends on the amount of water transferred per unit charge, which, unlike the electro-osmotic permeability, may vary over several orders of magnitude, depending on the water content of the soil, its cation exchange capacity, and its free electrolyte content. Mitchell (1973) discussed the fundamental nature of these relationships and gave the following principles:

1. A decrease in water content [illegible] a decrease in electro-osmotic efficiency.
2. Electro-osmotic water transport in inactive clays is greater than in active clays.
3. Water transport decreases with increasing electrolyte content.

In an actual field application the movement of water out of a soil mass and the resulting consolidation are of prime interest. Based on the analysis by Esrig (1968), which incorporates the assumptions that (a) the electrical and hydraulic contributions to fluid flow can be superimposed and (b) the soil properties are constant during consolidation, the pore water tension, u, developed in the soil at any point is given by

$$u = -\frac{k_e}{k_h}\gamma_w V \qquad (3\text{-}2)$$

where k_h is the hydraulic permeability, γ_w is the unit weight of water, and V is the voltage at the point. Since the total pressure at any point in a typical installation will not change during electro-osmotic treatment, the distribution of soil water tension represents the increase in effective stress. For one-dimensional consolidation we have

$$k_e \frac{\partial^2 V}{\partial x^2} + \frac{k_h}{\gamma_w}\cdot\frac{\partial^2 u}{\partial x^2} = m_v \frac{\partial u}{\partial t} \quad , \qquad (3\text{-}3)$$

where m_v is the soil compressibility and t is time. The solution for the case of an open cathode and a closed anode is given by

$$T_v = \frac{c_v t}{L^2} \quad , \qquad (3\text{-}4)$$

where $c_v = \frac{k_h}{m_v \gamma_w}$ is the coefficient of consolidation and T_v is the time factor. Since k_h controls the consolidation rate, fine-grained soils required longer times to obtain a desired degree of consolidation. Thus, the advantage of electro-osmosis in very fine-grained soils will be small due to the fact that the beneficial effect of k_e/k_h is largely offset by the low value for c_v. The optimum situation occurs when k_e/k_h is high enough to permit the development of reasonably high pore water tensions for reasonable electrode spacings (5 to 10 feet) and voltages (50 to 150 volts), but where k_h is high enough to enable consolidation within a reasonable period of time. These conditions appear best satisfied by silts, clayey silts, and silty clays.

A case history described by Bjerrum, Moum, and Eide (1967) indicates that the pattern of property changes in the field agreed with the theoretical predictions. Their data showed that a variety of electro-chemical effects may occur in addition to a simple generation of pore pressure and movement of water. As the water content of the soil gradually decreases in the vicinity of the anodes, the shear strength, liquid limit, and plasticity index increase. Other important consequences of the electro-chemical effects may include electrode decomposition, electro-chemical hardening of the soil, and generation of gas at the electrodes.

Based on the results of recent studies of consolidation by electro-osmosis (Mitchell, 1973), the simple theory of consolidation appears to be applicable only if the soil properties remain nearly constant during treatment; such a case is likely only in soils with very low compressibility (that is, in soils where electro-osmotic consolidation would probably not be used in the first place). In normally consolidated clays of high compressibility some modification of the theory is necessary to accurately predict the amount and rate of consolidation. The ratio k_e/k_h is likely to increase significantly during treatment, thereby leading to a greater amount and slower rate of consolidation than predicted by the simple theory. Mitchell (1973) demonstrated that two-stage electro-osmosis, wherein the electrode polarity is reversed after equilibrium is approached under the initial electrical field, results in an increase in the average consolidation pressure and more uniform water content between the electrodes, thereby enhancing the probability that relatively uniform soil properties will be developed between electrodes. An analysis shows that the electrode reversal technique may be economical in terms of both time and power consumption, and it also indicates that the superposition of consolidation by electro-osmosis and consolidation by direct loading can lead to a significant reduction in the time required for the dissipation of excess pore water pressures.

COMPACTION

When soil is in a loose condition, it is very compressible and has a low shear strength. One of the more effective methods for improving the properties of such a soil is compaction. For a given compactive energy the dry density increases as the water content increases; this is due to a break-down of soil clods and an increase in the workability of the soil. However, at a certain water content (termed the optimum water content) the dry density reaches a peak (termed the maximum dry density), and further increases in water content cause a decrease in the dry density because the voids of the soil are virtually filled with water (hence, much energy is used to move the water in the soil voids) and any additional water only replaces a portion of the soil solids, which have a higher specific gravity. For a given soil the so-called maximum dry density increases and the optimum water content decreases as the compactive effort is increased; therefore, both of these parameters are not absolute properties of the soil itself, but they are a function of the compactive effort. The compressibility and strength of a given soil are strongly related to its water content and density, and appropriate relationships among these parameters must be established. As a general rule, compaction requirements are stated in terms of a minimum density; however, the range of water content is sometimes specified in addition. The choice of compaction equipment depends primarily on the type of soil to be compacted, the water content, and the density requirements. In general, clay-like soils are compacted most effectively with sheepsfoot rollers; silty soils, with rubber-tire rollers, smooth-wheeled rollers, or sheepsfoot rollers; and granular soils, with vibratory rollers or vibro-flotation.

FIELD TREATMENTS

Dredge spoil may vary widely in its physical and chemical characteristics, but it generally contains some combination of silt and clay, organic materials, petrochemicals, domestic sludge, and industrial waste. In some cases conventional sanitary treatment processes may possibly be applied to these materials. In the following sections are reviewed several case histories concerned with field studies involving chemical flocculants, investigations for improving the density of dredged spoil, and sanitary treatment processes.

Field Studies with Chemical Flocculants

During May of 1968 the Dow Chemical Company (1968) used two Dow polyelectrolyte flocculants (Separan AP-273 and Purifloc C-31) to treat dredge spoil aboard the hopper dredge MARKHAM, which was engaged in maintenance work on the Saginaw Bay ship navigation channel for the Buffalo District of the U.S. Corps of Engineers. An attempt was made to rapidly precipitate undesirable contaminants in the hopper overflow during the dredging operation. However, the introduction of these chemicals into the intake pipes of the dredge prior to their discharge into the hoppers did not result in successful flocculation due to the excessive amount of solids. Spraying the chemicals directly into the hoppers during the filling process also produced unsatisfactory flocculation. A third method involved the application of the chemicals through a perforated pipe which was placed in the dredge above the overflow collection trough; the treated overflow material was discharged into the Saginaw Bay, and flocculation took place in the outflow pipe and in the bay. Eighteen series of samples, including both treated and untreated overflow material, revealed a definite improvement in the settling characteristics of the solids when the polymers were added. The optimum concentrations of flocculants were estimated at 8 mg/ℓ for Separan AP-273 and 35 mg/ℓ for Purifloc C-31.

After a 15 minute settling time, residual suspended solids and turbidity in the Bay were reduced to as much as one-fifth of the levels that were present without treatment; improved ortho-phosphate and BOD reductions were also noticeable with treatment. The numbers of total coliform bacteria were very low, despite the dredging activity; normally the coliform counts are high, but chemical flocculation is capable of removing the majority of these indicator organisms. The cost of chemicals for treating this overflow material, which contained approximately 10% solids, was about $0.09 per 1000 gallons, or about $0.02 per cubic yard of dredged material. Laboratory comparisons showed that settling rates were higher with polyelectrolytes than with common Fe^{+3} and Al^{+3} coagulants. Iron and aluminum salts generally produced poor flocs, unless massive doses were applied.

The Dow Chemical Company (1968) also conducted field trials to evaluate the effect of chemical flocculants on the effluent from the Riverside dredge spoil area in Toledo, Ohio. A two-acre corner was diked off to form a clarification pond, and Supernatant water from the main disposal area was discharged into the clarification pond through a 250-foot long corrugated metal trough in which the chemicals were added.

Before undertaking the field test, many laboratory tests were conducted with different coagulants and acids on materials with a wide range of suspended solids. It was found that flocculation was most effective with Purifloc C-31 when suspended solids were at a concentration of about 8,000 mg/ℓ and very good at concentrations up to 20,000 mg/ℓ; above this level the effectiveness decreased rapidly. Below the 8,000 mg/ℓ level, the effectiveness also decreased, but the addition of ferric chloride improved the flocculation; at low concentrations of suspended solids, a combination of ferric chloride and Purifloc C-31 proved to be best.

The concentration of suspended solids in the water discharged into the coagulation pond was only 60 mg/ℓ during the 48-hour field test at the disposal area; it was necessary to treat this material with 33 mg/ℓ of ferric chloride and 7.5 mg/ℓ of Purifloc C-31. Suspended solids were reduced to as little as 10 mg/ℓ; the total phosphates decreased from 0.16 mg/ℓ to 0.10 mg/ℓ; and the total coliform count dropped from 14,700 to 9,000 counts per 100 mℓ. The chemical oxygen demand showed a slight increase, but at the same time dissolved oxygen content showed a corresponding slight increase and was always considerably in excess, so that septicity or low oxygen content never occurred. The cost of chemicals was about $0.10 per cubic yard of dredged spoil. Researchers from the Dow Chemical Company believe that the concentration of suspended solids was too low for an optimum test. Actually there should be little need for coagulation with so low a level of suspended solids; with a higher concentration of suspended solids it is probable that the ferric chloride could be eliminated and the same results could be obtained by use of the same amount of polymer (Purifloc C-31).

Studies to Increase the Density of Dredged Spoil

In an attempt to increase the quantity of solids in a dredge load, the Philadelphia District (1969) of the Corps of Engineers made a study of three methods. Although the aim of this current study is to improve the engineering properties of spoil material inside the diked area, the initial conditions, surrounding situation, and transformation periods are different from those that exist during the on-board treatment of the dredged mixture; however, the ideas and technology of these methods may nevertheless be useful.

Gravity Precipitation -- For fine materials having a density of about 1,060 gm/ℓ or less, it was found that the top one-third of a hopper load of dredged material became relatively clear in an 8-hour period due to settling of solids; however, the density of efficiently dredged spoil would usually exceed this value.

Chemical Precipitation -- With a view towards accelerating the sedimentation rate of dredged materials on board a dredge by use of (a) chemical precipitants, (b) flocculating agents, or (c) ion exchange, the Dow Chemical Company, Rohm and Haas Company, Drew Chemical Company, and Rutgers University each investigated the problem during a series of field trips and a program of laboratory tests. They all concluded that the innate density of the dredged mixture exceeded that at which chemical agents or catalysts could be effective. This conclusion confirms that of similar investigations performed by the Philadelphia District of the Corps of Engineers in 1958.

Hydrocyclone -- Another means to separate solids from water in a dredged mixture involves the use of a centrifuge. However, the size of the equipment and the amount of the energy required to obtain the separation of a fine-grained mud suspension from the water-mud mixture becomes impracticable.

Sanitary Treatment Processes

For some extremely heavily polluted maintenance dredgings, it may be necessary or desirable to treat them in separate treatment plants before disposing of them in the open waters or diked spoil areas. Nebolsine, Toth, McPhee, and Associates (1968) was authorized by the Buffalo District of the Corps of Engineers to study the engineering feasibility of various methods for treating dredged materials to render them unpolluted when deposited into the open waters or diked spoil areas. For the purpose of their study it was assumed that the stabilization of the biological activity of the sludges or slurries was the prime criteria, and, once stabilized, these sludges or slurries would be acceptable for disposal in the lakes or on dry land.

About 15% of the dredged materials are sand size or larger; although this fraction is fairly clean, it does contain some polluted material that must be removed. These large particles would separate from the dredgings as they are pumped from the dredges into a containment area, and the remaining material would be allowed to settle for several days and consolidate. The excess water would be decanted and treated before being discharged into the nearby harbors. Various processes were investigated to treat the remaining solids, which contain about 10% organic material; these included anaerobic stabilization, aerobic stabilization, chemical oxidation, wet oxidation, etc. Although the process of stabilizing the spoil inside the diked containment area is different from that used in sanitary stabilization processes, Krizek and Karadi (1973), using the results from an extensive series of field and laboratory tests on dredge spoil and the associated water samples from one harbor area, concluded that the disposal of polluted dredging wastes in a containment area is effective in reducing the amount of pollutants that re-enter the lake waters, at least on a short-term basis. Despite the fact that the sanitary stabilization method in itself may not be of major concern, most of the significant pollution parameters have been checked in most cases throughout this current investigation to evaluate the quality of the leachates.

SUMMARY OF EXPERIENCE WITH VARIOUS CHEMICAL STABILIZING AGENTS

Table 3-2 gives a brief summary of possible soil stabilization chemicals. Although all of the additives listed will cause flocculation and most will result in a cementation or linking reaction, not all of these chemicals have been tested with actual dredging materials; therefore, an explicit comparison of results is virtually impossible. As far as inorganic chemical stabilizing agents are concerned, most of the work reported in the literature emphasizes soil stabilization in highway construction practice, and results obtained for such conditions may be

Table 3-2

Summary of Experience with Selected Stabilization Chemicals

Additive	Type of Soil	Level of Additive	Major Stabilization Mechanism	Improvements in Engineering Properties	Observations and Remarks	Reference
Lime	Oklahoma Soil (plastic clay) Illinois Soils (silty clay and silty loam) Louisiana Soil (organic soil with 20% organic matter)	About 2% of dry weight of solids	Cation exchange Flocculation and agglomeration Cementation Pozzolanic reaction	Shear strength increases CBR increases Plasticity decreases Binder content decreases Shrink-swell decreases Water plugging increases	High temperature or catalyst can speed the curing process Test conditions were similar to normal soil stabilization in field practice Organic matter in soils does not block the pozzolonic reaction Coarse quick-lime is more effective, but a loose-curing period is required	Marks & Haliburton (1970) Drake & Haliburton (1972) Alexander et al (1972) Thompson (1966) Arman & Munfakh (1972)
Chlorides	Iowa Soil (soil-aggregate mixture)	0.5 to 2.0% of dry weight of solids	Lubrication Flocculation Moisture retention Cementation Surface tension Crystallization	Shear strength increases Density increases Freezing point decreases Water plugging increases	Special for stabilization of road aggregates Test conditions were similar to normal soil stabilization in field practice	Gow, Davidson & Sheeler (1960)
Inorganic Acids, Alkalis, and Mono- or Divalent Hydroxides	Kaolin Montmorillonite	10% of dry weight of solids	Surface coating of fabric units Reinforcement of soil by product formation		Reactions of additives on kaolin and montmorillonite are not necessarily similar Test conditions were similar to normal soil stabilization in field practice	Ingles (1970)
Substituted Benzine Ring Compounds	Gila Clay (<2μ) National Standard Bentonite	20 millimoles per 30 grams dry weight of solids	Interlayer absorption Flocculation Cross linking		Interlayer absorption and naturally existing organics do not insure flocculation Used on thin slurries of 2.5% soil and 0.5% clay	Chang & Anderson (1968)
Krilium and Polyvinlalcohol	Urrbrae Red-Brown Earth (clay-roam) Solidized Solonetz (loamy sand)	25 mℓ of 0.4% additive solution mix with 100 gms of dry soil	Aggregation Lining soil pores	Soil-water diffusivity increases 1.5 to 3.0 times	Special for stabilization of agricultural lands After mixing, the soil was dried; then, the liquid was infiltrated	Kijne (1967)
AP-273 Purifloc C-31	Great Lakes Dredging and Sediments (clayey silts)	8 mg/ℓ 35 mg/ℓ	Flocculation Coagulation	Suspended solids decreases BOD decreases Coliform count decreases	Can cause very quick flocculation with 8 g/ℓ concentration of slurry Tested on 20,000 to 60,000 mg/ℓ slurries Special for water quality control	Dow Chemical Company (1968)

quite different from those that are achieved with dredgings. As another example, most of the organic chemical stabilizing agents listed in the literature were found to be very effective in the flocculation of very thin soil slurries or dredging slurries, but the mechanisms described may be much less effective when applied to actual dredging materials at concentrations normally encountered, and the effects on the final engineering properties of the sediments are not known. Each investigator studied a given additive from a different point of view and for a different purpose; thus, terminology and interpretations may not be compatible.

CONCLUSIONS

In a typical diked containment area polluted maintenance dredgings take the form of a thin slurry with a water content of several hundred percent near the top of the mass and a soft sediment with a water content about a hundred percent near the bottom of the area. The deposits, which are frequently located in low lying swampy areas with poor drainage, often have a depth of 10 or 15 feet and are gas generating in nature. These fine-grained organic deposits generally have a low strength and permeability, and the consolidation of the layer may not be predictable by use of conventional consolidation theories and test data. Hence, this is not a common problem with an extensive history, and little is found in the literature to shed much light on its solution. In addition, during and after the filling process various water pollution problems may result.

Although various dewatering techniques are effective and technically feasible after the dredge spoil has been deposited in the containment area and developed some shear strength, the application of these techniques is very much limited while the deposits are soft. This problem may be partly alleviated by the use of certain chemical additives prior to the mixing-disposal process. These additives may alter the initial soil structure and/or the properties of the final settlement. Moreover, they may aid in retaining the pollutants in the sediment due to flocculation and coagulation effects, thereby reducing the pollution potential of the effluent and the leachate. With regard to the flocculation effect, most of the organic chemical stabilizing agents (benzene ring compounds, polyelectrolytes, etc) listed in the literature reacted effectively in a very thin soil solution or dredging slurry, but the described mechanism for this reaction may be virtually inoperative when applied to thicker dredging materials; furthermore, their effects on the final properties of the sediment are not known. As far as inorganic chemical stabilizing agents are concerned, most of the work reported in the literature emphasizes the state of normal soil stabilization processes in field practice (that is, mixed at optimum water content, compacted, and moist-cured); this state differs considerably from that associated with the normal sedimentation-consolidation processes of dredge spoil. Thus, the effectiveness of these chemical stabilizing agents may be different when added to dredging materials, and a study of the entire sedimentation-consolidation process of the chemically treated dredging material is necessary. In addition, the technical and economical feasibility of using various other stabilization methods (compaction, electro-osmosis, vacuum, etc) must be assessed.

CHAPTER 4

MATERIALS INVESTIGATED

The dredgings studied in this experimental program are primarily fine-grained clayey silts in the form of slurries or thick muds with water contents from 100% to 500%; they are from harbor areas around the Great Lakes and have generally been classified as polluted. Although most of the samples were obtained from discharge pipe while the dredge was pumping the spoil into the disposal area, a few samples were taken at other points in the dredging and disposal cycle. Most of the materials were dark gray to black in color and contained a substantial percentage of organic matter. Very often gases were generated as the organic matter in these materials digested and decomposed during storage and/or testing. Since the samples were collected in the form of either a thin slurry or a thick mud, it was especially difficult to obtain a representative sample to test in the laboratory; accordingly, each series of tests always includes a blank specimen and a record of the initial condition for each test specimen. Included in this chapter are a description of the source and nature of all dredging samples tested, collection methods, notation employed, engineering characteristics, and storage and handling procedures.

SOURCE OF SAMPLES

Ten dredging samples were collected from five cities in the vicinity of the Great Lakes; seven of these were slurry samples taken from discharge pipes and three were thick muds taken from bottom sediments or dredging disposal areas. Samples are designated by a three-part symbol; the first part is a letter that indicates the general consistency of the sample (C materials are thin slurries, and D materials are thick muds); the second part is a chronological number that denotes a specific sample within any given consistency group; and the third part consists of two letters that identify the city and state from which a particular sample was obtained (CO = Cleveland, Ohio; CI = Chicago, Illinois; DM = Detroit, Michigan; MM = Monroe, Michigan; and TO = Toledo, Ohio). Table 4-1 gives a brief description of the samples tested in this experimental program, and Figures 4-1 through 4-7 show the approximate locations from which each sample was obtained.

SAMPLING PROCEDURES

The problems associated with obtaining representative samples from the discharge pipes and from the soft bottom sediments or soft materials in a disposal area are quite different, and two different sampling methods were employed to obtain samples in these two situations. A detailed description of the sampling methods used in this study have been reported by Krizek, Karadi, and Hummel (1973).

Samples from Discharge Pipe

In general, the spoil material passing through the discharge pipe during approximately the first and last five minutes of each load was not representative, because the dredge usually pumps large quantities of ambient water through the pipe to clean it before and after each use. Hence, it was necessary to observe the discharge and wait until it appeared reasonably uniform before collecting any samples. The sampling procedure involved either the placement of a container directly in the slurry jet from the pipe or the use of a 3-inch diameter tube that was fixed to the end of the discharge pipe and had a 90° bend to divert some of the slurry into a container.

Table 4-1

Summary of Dredging Samples Tested

Sample	Date Obtained	Location
C2DM	12/7/70	Material from discharge pipe at Grassy Island.
C3TO	12/10/70	Material from discharge pipe at Penn 8.
C5CO	12/11/70	Material from discharge pipe at diked area.
C22TO	7/2/71	Material from discharge pipe at Island Site.
C27MM	11/11/71	Material from discharge pipe at diked area.
C28CI	7/31/72	Material from discharge pipe at Calumet disposal site.
C80TO	12/4/72	Material from discharge pipe at Penn 7.
D1DM	12/8/70	Bottom sediments from Rouge River by flap valve sampler.
D3TO	12/9/70	Soft sediments from Riverside Site by shovel
D4CO	12/11/70	Bottom sediments from Cuyahoga River by shovel from scow.

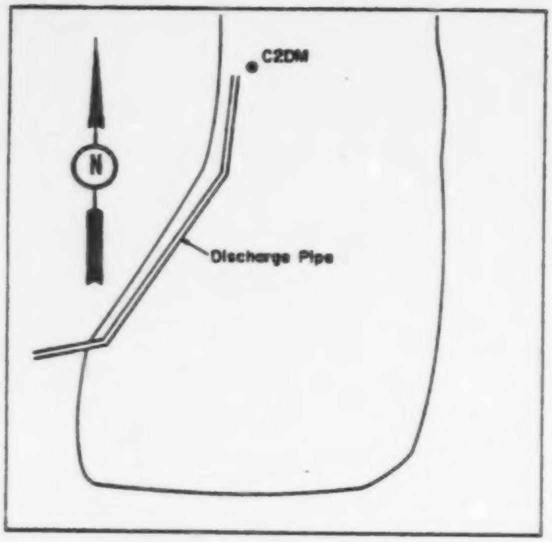

C2DM
N
Discharge Pipe

Figure 4-1. Grassy Island Disposal Area

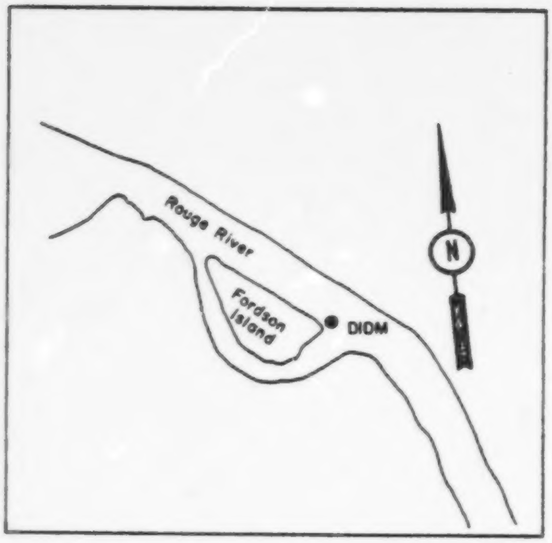

Rouge River
Fordson Island
DIDM
N

Figure 4-2. Fordson Island Disposal Area

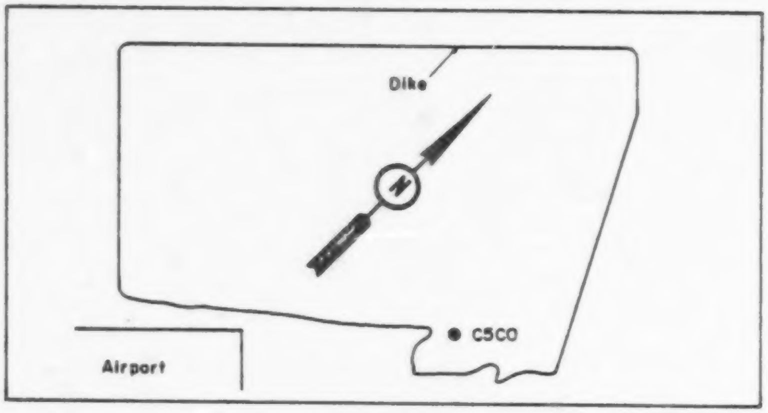

Dike
N
C5CO
Airport

Figure 4-3. Cleveland Harbor Disposal Area

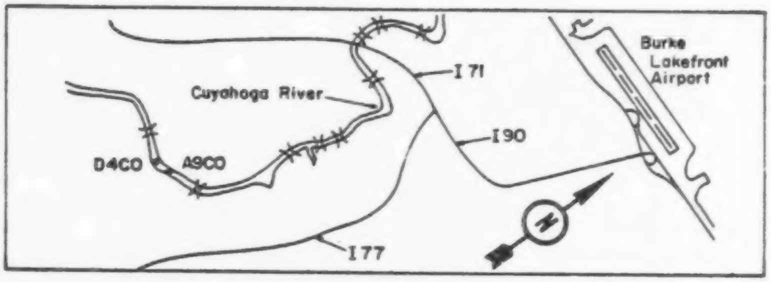

Cuyahoga River
I 71
I90
I77
D4CO
A9CO
Burke Lakefront Airport
N

Figure 4-4. Cuyahoga River Disposal Area

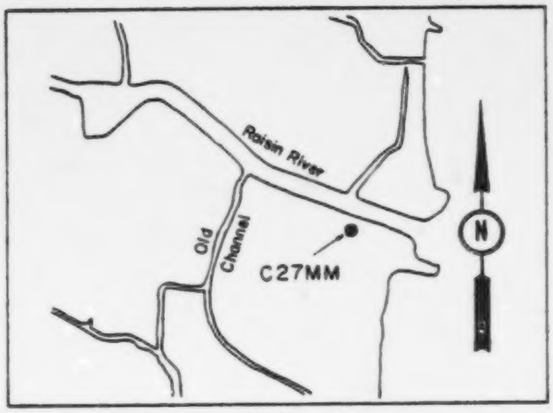
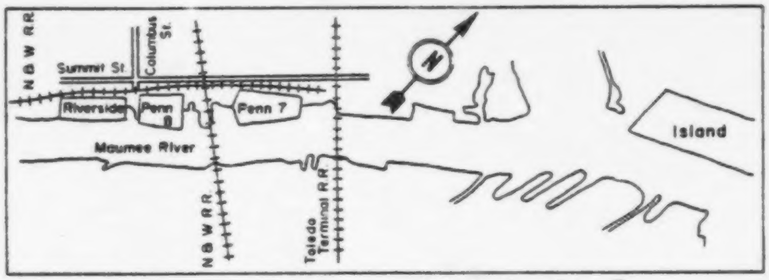

Raisin River
Old Channel
C27MM
N

Figure 4-5. Monroe Disposal Area


N&W RR
Summit St.
Columbus St.
Riverside
Penn 8
Penn 7
Maumee River
N&W RR
Toledo Terminal RR
N
Island

C3TO from Penn 8
C22TO from Island
C8OTO from Penn 7
D3TO from Riverside

Figure 4-6. Toledo Disposal Areas

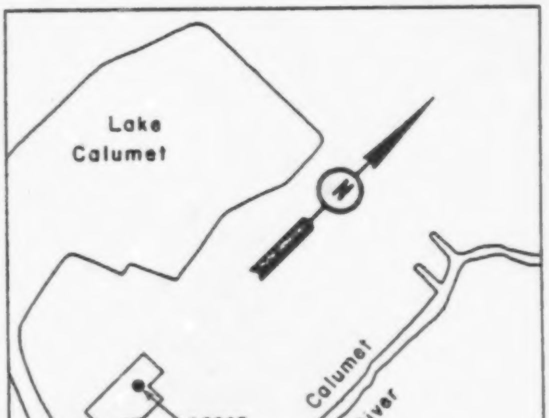

Lake Calumet
N
C28CI
Calumet River

Figure 4-7. Calumet Disposal Area

Samples of Soft Sediments

Samples of soft sediments were obtained by means of a custom-designed flap valve sampler shown in Figure 4-8. When this sampler is pressed downward by means of light-weight aluminum rods through any overlaying water into the soft sediment to be sampled, the bottom flap valve opens on the downward thrust, thereby allowing water and sediment to enter the tube. Vent holes in the top cover plate of the tube allow the trapped water to escape as the sediment is forced into the tube. The sampling depth can be adjusted by the length of rod used. Upon raising the sampler, the hinged bottom flap valve closes and forms a nearly watertight seal against its seating ring, thus allowing good sample retrieval. When the tube with the sample is placed on the working platform, the top plate is removed and the sample is emptied into a container. Due to the difficulty associated with handling the rod and pushing the sampler into place, it is necessary to work from a relatively stable platform. If the water was not too deep, as was the case for the Riverside disposal area at the time of sampling, a shovel was used very effectively to collect samples.

STORAGE AND HANDLING

Care in the storage and handling of dredging samples is important, because biological degradation, chemical digestion, and other environmental factors may change the engineering properties of these materials, and the behavior of laboratory samples may not represent the behavior of insitu sediments. As reported by Silver (1971) for a highly organic dredging material from Waukegan, Illinois, the volume of the sample increased about 20% due to the large quantities of gas that had developed by storing the sample several weeks at room temperature. The effects of these factors on the engineering properties of dredgings are not well understood, and their

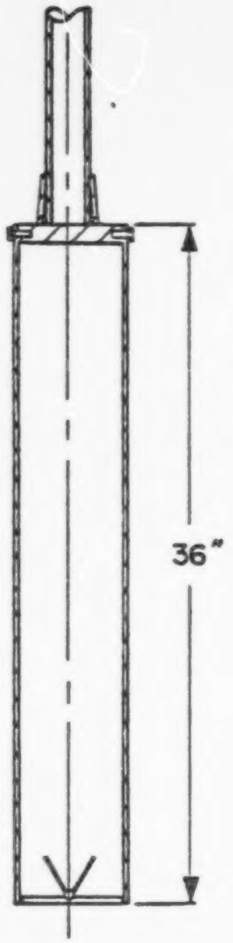


Figure 4-8. Flap Valve Sampler

complete elimination might remove a significant parameter from the test results. Ideally, new bacterial growth should be suspended in dredging samples during storage, and existing levels should be maintained until the experiment is begun; in this way some portion of the biological degradation which occurs during the actual field situation would continue during the test. In general, the samples collected for this investigation were transported from the field to the laboratory at temperatures just above freezing; during the early stages of the study (until January of 1973) all samples were stored at 4°C, but during the latter stages the samples were stored either inside at room temperature (January through June of 1973) or outside at prevailing temperatures for Evanston, Illinois (after June of 1973). Unless otherwise stated, all tests were conducted at room temperatures, and most of the tests were started prior to January of 1973. Based on observations throughout the period described above, the dredging materials tested in this investigation did not undergo any noticeable changes either during storage or testing.

ENGINEERING CHARACTERISTICS

Table 4-2 summarizes the engineering characteristics of the ten samples used in this investigation. The natural water content is the water content of the sample as it was obtained from the field. The specific gravity of solids was determined in accordance with the procedure outlined by Lambe (1951); although most values of specific gravity are between 2.60 and 2.70, some values are as low as 2.51, possibly due to traces of slag, petrochemical wastes, wood, and/or plant matter. The grain-size distributions and Atterberg limits of all samples are reasonably similar (except for Sample C28CI, which is coarser than the others).

Table 4-2

Engineering Characteristics

Sample	Natural Water Content (%)	Specific Gravity	Grain Size Distribution			Atterberg Limits	
			Sand (>0.06 mm)	Silt (0.06 mm to 0.002 mm)	Clay (<0.002 mm)	Liquid Limit (%)	Plastic Limit (%)
C2DM	134	2.63	12	65	23	49	32
C3TO	136	2.72	10	66	24	51	33
C5CO	370	2.58	17	63	20	56	37
C22TO	470	2.56	10	50	40	69	40
C27MM	800	2.51	13	52	35	59	49
C28CI	350	2.70	95	3	2	--	--
C80TO	530	2.66	8	51	41	66	36
D1DM	97	2.57	20	50	30	56	39
D3TO	116	2.70	17	50	33	46	32
D4CO	101	2.74	19	55	26	48	34

Table 4-3 gives the results of mineralogical and physico-chemical analyses on these samples. The mineralogical composition of the clay-size particles (less than 2 microns) was determined by X-ray analyses with heat and ethylene glycol treatments. Of the clay mineral present, the quantitative amounts of illite, kaolinite, and mixed layer minerals were about 50% to 70%, 15% to 25%, and 20% to 35%, respectively; however, a few of the samples had only trace amounts of mixed layer minerals. The carbonate content was determined by the gravimetric (weight loss) method, and, of the carbonates present, the quantitative amounts of calcite and dolomite were about 60% and 40%, respectively. The hydrogen ion concentration was measured by means of a Beckman pH meter on the regular scale. The organic carbon content was determined by the Walkley-Black method (Black, 1965). For most of the samples tested the organic carbon ranged from about 5% to 10%, and the materials would be classified as OH according to the Unified Classification System. The cation exchange capacity was determined by the ammonium acetate method (Davison and Sheeler, 1952), and values were about 15 meq/100 gm, which is consistent with the clay minerals present. The identification of exchangeable ions and the relative amounts of each were made on the ammonium acetate extracts obtained from the leachates of the cation exchange capacity tests. Atomic absorption was used to determine the amounts of calcium, magnesium, iron, and manganese; flame emission was employed for sodium and potassium; and solution transmission was used for aluminum.

Most of the physical, chemical, and biochemical parameters related to the pollution potential of these samples are listed in Table 4-4. The methods for determining these parameters have been described in detail by Krizek, Karadi, and Hummel (1973), and certain modifications to these

Table 4-3

Mineralogical and Physico-chemical Analyses

Sample	Clay Mineral (%)			Carbonates (%)	Calcite (%)	Dolomite (%)	Hydrogen Ion Concentration (pH)	Organic Carbon (%)	Cation Exchange Capacity (meq per 100 grams of dry material)	Ions (meq relative to milliequivalents of Calcium)						
	Illite	Kaolinite	Mixed Layer							Aluminum (A)	Calcium (Ca)	Magnesium (Mg)	Iron (fe)	Sodium (Na)	Potassium (K)	Manganese (Mn)
C2DM	60	20	20	29.3	19.0	10.3	7.6	8.8	15.1	3.3	1.0	0.31	0.008	0.170	0.030	Trace
C3TO	50	15	35	35.6	19.7	15.9	7.4	3.6	18.2	1.7	1.0	0.17		0.060	0.018	Trace
C5CO	60	20	20	38.6			8.0	10.5	15.3	2.8	1.0	0.21		0.050	0.030	Trace
C22TO								5.4								
C27MM								8.8	14.4							
C28CI																
C80TO																
D1DM	65	35	Trace	24.6			7.2	10.1	14.0	3.7	1.0	0.15		0.060	0.033	Trace
D3TO	50	15	35	28.1	16.9	11.2	6.9	5.1	15.8	1.4	1.0	0.32		0.050	0.023	Trace
D4CO	75	25	Trace	39.9			7.8	8.8	11.9	2.6	1.0	0.19		0.070	0.028	Trace

Table 4-4

Chemical Analyses of Sample Tested

Sample	Total Solids	Total Volatile Solids	Total Suspended Solids	Total Volatile Suspended Solids	Turbidity	Acidity	Hydrogen Ion Concentration (pH)	Oxidation-Reduction Potential (Eh)	Dissolved Oxygen (DO)	Biological Oxygen Demand (BOD)	Chemical Oxygen Demand (COD)	Organic Nitrogen (N)	Ammonia (NH_3) Nitrogen (N)	Nitrite (NO_2) Nitrogen (N)	Nitrate (NO_3) Nitrogen (N)	Total Phosphate (PO_4)	Soluble Phosphate (PO_4)
	%	%	%	%	JTU	mg/gm		mv	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm
C2DM	12.25	2.09	12.22	2.08	>1000		7.7										
C3TO	13.90	1.55	12.87	1.54	>1000		7.4										
C5CO	14.05	1.96	14.01	1.95	>1000		7.7										
C22TO	16.22	2.07	16.15	2.05	>1000		7.3										
C27MM	11.37	1.90	11.31	1.83	>1000		7.3										
C28CI	1.46	0.21	1.43	0.20	>1000		8.2										
C80TO	14.65	1.56	14.62	1.54	>1000		7.5										
D1DM	13.10	2.81	13.06	2.79	>1000		7.6										
D3TO	13.45	1.61	13.39	1.59	>1000		7.4										
D4CO	12.42	1.64	12.35	1.62	>1000		7.8										

Sample	Grease	Hydrocarbons	Aluminum (Al)	Arsenic (As)	Calcium (Ca)	Copper (Cu)	Total Iron (Fe)	Soluble Iron (Fe)	Potassium (K)	Silica (SiO_2)	Sodium (Na)	Sulfide (S)	Cadmium (Cd)	Cyanide (CN)	Lead (Pb)	Mercury (Hg)	Phenolics
	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	µg/gm	µg/gm	µg/gm	µg/gm	µg/gm
C2DM					21.7	0.18	20.8		2.0	566	0.49		4.6		380	410	
C3TO					20.2	0.03	13.3		2.2	739	0.37		1.6		110	280	
C5CO					3.2	0.20	26.2		1.0	683	0.42		16.1		360	160	
C22TO					15.0	0.40	13.5		2.4	735	0.43		3.1		130	300	
C27MM					21.2	0.23	14.6		1.3	681	0.38		2.9		210	260	
C28CI					38.2	0.34	141.0		2.0	395	1.23		-		740	840	
C80TO					17.5	0.04	14.0		2.3	759	0.41		2.5		120	300	
D1DM					14.2	0.17	18.1		1.0	511	0.38		6.6		440	490	
D3TO					17.2	0.05	15.2		2.3	742	0.43		2.9		110	340	
D4CO					6.6	0.13	21.3		1.3	540	0.40		21.8		500	370	

procedures are discussed in Chapter 7. A comparison of these data with criteria suggested by Brown and Keffer (1971) and O'Neal and Sceva (1971) indicates that each of the ten samples would be classified as polluted.

The classifications of these samples according to five engineering classification systems are given in Table 4-5. According to the Unified Soil Classification System for OH and OL soils, the dry strengths (crushing characteristics) are medium, the dilatancy (reaction to shaking) is very slow, and the toughness (consistency near the Plastic Limit) is slight. From the AASHO classification for A-7 and A-7-5 soils, their general rating as subgrade materials ranges from fair to poor. The Agriculture Textural Classification of these materials categorizes them as silty loams, silty clay loams, clay loams, or silty clays. Based on the Federal Aviation Agency Classification, E-7, E-8, E-9, and E-10 soils are rated in the middle to lower categories, and the Corp of Engineers Frost Susceptibility Classification indicates that F-3 and F-4 soils have high degrees of frost susceptibility. In general, Sample C28CI is an exception to the foregoing generalizations; it is a fine-grained cohensionless soil which is reasonably good for use as a foundation material.

CONCLUSIONS

Based on the results of engineering classification tests and mineralogical and chemical analyses, it can be generally concluded that the dredging samples used in this investigation are polluted according to current environmental criteria and are rated as medium to low quality soils for engineering purposes. Since most dredgings are biochemically active to some degree, it is desirable to test a blank reference specimen with each series of tests, and appropriate care must be exercised in their storage and handling; in addition, the interpretation of test data must

Table 4-5

Engineering and Agricultural Classifications

Sample	Unified	AASHO	Agricultural or Textural	FAA	Frost Susceptibility
C2DM	OL	A-7-5(12)	Silty Loam	E-7	F-3
C3TO	OH	A-7-5(13)	Silty Loam	E-8	F-3
C5CO	OH	A-7-5(15)	Silty Loam	E-8	F-3
C22TO	OH	A-7-5(20)	Silty Clay	E-10	F-3
C27MM	OH	A-7(12)	Silty Clay Loam	E-9	F-4
C28CI	--	A-1-b	Sand	E-1	F-1
C80TO	OH	A-7-5(20)	Silty Clay	E-10	F-3
D1DM	OH	A-7-5(15)	Clay Loam	E-8	F-3
D3TO	OL	A-7-5(11)	Silty Clay Loam	E-7	F-3
D4CO	OL	A-7-5(11)	Silty Loam	E-7	F-3

be approached with an appreciation for the possible alterations in the engineering properties caused by chemical digestion and biological degradation.

CHAPTER 5

FLOCCULATION AND SEDIMENTATION TESTS

The addition of a flocculating agent to a soil suspension causes a flocculation or joining together of fine-grained soil particles, thereby increasing the effective particle sizes of the material. According to Stokes' Law, these larger flocs then settle more rapidly from the suspension to form a relatively large sediment volume. The introduction of flocculating agents to polluted maintenance dredgings during the process of disposal into a diked containment area may effectively increase the sedimentation rate and decrease the amount of suspended solids in the effluent water. In addition, the flocculation of suspended solids may result in increased retention of pollutants in the disposal area, further improving the quality of the effluent water. The tests described in this chapter were conducted to evaluate the flocculation effect of various chemical additives on dredge spoils with different compositions; the additives to be investigated were chosen after a comprehensive review of the literature, and the test results were used to select the more promising additives for further study of their effects on flocculation, drainage, and stabilization of dredging wastes and on pollution retention characteristics.

BACKGROUND AND RELATED WORK

Most of the dredged materials used in this investigation contained about 30 percent clay size material (less than 0.002 mm); it is this portion of the material that is primarily affected by the addition of chemical flocculating agents. Clays have some special physico-chemical properties, that are due chiefly to the influence of (a) a high specific surface area and (b) an electrical charge on the basic layered silicate structure of the clay minerals. The high specific surface area is a consequence of the small particle size and the platy or elongated shape of clay particles. In the layered structure the area of the face surface is much larger than that of edge surface, and, because of the basic layered mineral structure, the face surfaces differ from the edge surfaces and have distinctive properties. The electrical charge associated with the clay particles is believed to stem from two major mechanisms; these are (a) isomorphous substitution and (b) broken bonds. Isomorphous substitution accounts for most of the charge in 2:1 and 2:1:1 layer minerals, but only a minor part in the 1:1 layer Kaolinites. The unsatisfied valence charges at the edges of the particles, termed broken-bond charges, attract hydrogen or hydroxl ions from the pore fluid; therefore, the type of absorbed ion is dependent on the relative ionic concentrations and the pH of the solution. Accordingly, the charges at the edges of the particles are reversible. In the case of Kaolinite it is believed that the peculiar flocculation observed at pH values less than 4 is a result of the attraction of positive edge charges and negative face charges. Above a pH of 4 the edges are also negatively charges, and a net negative charge results, thereby causing dispersion.

The charge on the clay particles is balanced by ions of opposite charge, known as counter ions, which are situated in the solution surrounding the particle. The concentration of the counter ions decreases with increasing distance from the surface of the clay particle. The charge on the surface of the particle, together with the charge due to the balancing counter ions, is called the elctrical double layer. The nature and extent of the double layer is affected by the concentration and composition of the electrolyte solution, the density of charge on the surface of the particle, and the temperature.

The susceptibility of clay suspensions to flocculation by cations can be explained in terms of a balance between attractive and repulsive forces. At high electolyte concentrations and/or with high valence counter ions, the dimension of the double layer is reduced. This has the effect of reducing the repulsive forces between particles at any given particle separation. The van der Waals attractive forces between particles, on the other hand, are not strongly affected by changes in the electrolyte concentrations or the ion valence. These are short range forces which are inversely proportional to the fourth power of the distance between the particles, and they become operative when the double layer is compressed sufficiently and the particles come within their range. These forces of attraction cause particle adhering or flocculation, whereby the size of the kinetic units rapidly increases, the Brownian movement decreases, and the gravitational forces exert a dominant influence on large size flocs, which soon settle from suspension.

Flocculation can also be induced by the addition of organic compounds, which lower the dielectric constant of the medium, coat the clay particles, and form links between particles. A more detailed description of the physico-chemical behavior of clay soils can be found in Chapter 3.

The Dow Chemical Company (1968) made some laboratory investigations to determine the amounts of certain proprietary polymers (Purifloc C-31 and Separan 273) and inorganic flocculants (iron and aluminum salts) that would be required to flocculate suspended solids in the overflow from a hopper dredge during maintenance dredging at the mouth of the Saginaw River. Normally some of these suspended solids remain in suspension and migrate towards the shoreline, where they settle to form undesirable sludge banks. In this study two methods were used to observe flocculation effectiveness; one was to make an initial 10:1 dilution of dredge overflow material with bay water and then flocculate the diluted slurry, and the other was to add the flocculant to the undiluted overflow and then add the dilution water. The flocculation schedule consisted of 10 seconds contact and flash mixing by revolving the 100 mℓ cylinder on the mechanical flocculator at 100 rpm, followed by 2 minutes of flocculation at 40 rpm. An additional 2 minutes of dynamic settling at 5 rpm was allowed before samples of the supernatant were withdrawn for turbidity readings.

The laboratory test results showed that, when the overflow solids were treated prior to any bay water dilution, satisfactory flocculation required either 20 mg/ℓ Purifloc C-31 or 100 to 130 mg/ℓ Fe^{+3} or >130 mg/ℓ Al^{+3}; however, when the slurry was diluted with bay water before adding the flocculant, the chemical demand was reduced to 10 mg/ℓ Purifloc C-31 or 40 mg/ℓ Fe^{+3} or 10 mg/ℓ Al^{+3}. Settling rate comparisons showed that the organic flocculants were more successful than the inorganic salts in achieving rapid sedimentation; poor floc formation by the inorganics was responsible for this difference. Massive doses of Fe^{+3} or Al^{+3} salts were required before acceptable clarity could be attained.

The Dow Chemical Company (1968) also made some investigations in the Penn 8 and Riverside Spoil Areas in Toledo, Ohio. Besides the Purifloc C-31 tests, many other combinations were tried. Addition of hectorite clay (25 to 50 mg/ℓ) was found to be quite beneficial, and it was found that water which has a high concentration of suspended solids (20.3 gm/ℓ) is often easier to clarify than water with a much lower concentration (0.4 gm/ℓ). One theory developed to explain this phenomenon is that it is necessary to have particle to particle impingement in order to have them grow into large enough clusters to settle; if the concentration of particles is low, the frequency of collisions is very low and flocs do not form as readily. If the water has too many solids in suspension (40.5 gm/ℓ), it becomes difficult to distribute the chemical throughout the slurry before it becomes absorbed; hence, some of the solids remain untreated, and a turbid supernatant results.

The final laboratory effort on the Toledo dredging slurries involved an attempt (a) to correlate the settling rate of a given floc with the size of that floc and (b) to determine whether this relationship could be changed. The results showed that there was a definite correlation between settling rate and size of floc. The final clarity or flocculation efficiency is a function of the degree and length of turbulence. It was observed that the majority of the flocs formed by treatment with Purifloc C-31 were in the range of 100 microns to 700 microns, and most of the solids had settling rates greater than 0.1 ft/min; this is a very high settling rate, and it suggests that a rather small clarification basin can be used.

SAMPLE PREPARATION AND TEST PROCEDURES

The characteristics of the dredging materials used in this investigation and their sampling and storing procedures have been discussed previously; because of possible changes in material properties during storage due to biological action and decomposition of organics, all samples for a given series of tests were taken from storage and processed at the same time, including untreated blank samples for control purposes. The procedures for the flocculation and sedimentation tests were as follows:

1. The material in the storage container was thoroughly mixed, and a representative sample was taken.
2. The concentration of solids (gm/cc) was determined, and the volume of material for a sample containing 50 grams of solids was calculated.
3. For each individual test a sample containing 50 grams of solids was taken, and the required amount of chemical added. The samples were processed as specified in ASTM Designation D422-63 "Standard Method for Particle Size Analysis of Soils", with the exception that a dispersing agent was not added to the treated samples. Blank, or untreated, samples were prepared both with and without a dispersing agent.
4. After processing, the sample was transferred to a 1000 cc hydrometer jar and the jar filled to the 1000 cc mark with distilled water; the material was mixed and then allowed to stand for 24 hours to permit chemical interaction to occur.
5. After 24 hours the sample was thoroughly mixed and a standard grain size distribution test conducted (ASTM 422-63) using a 151 H hydrometer; the volume of sediment was recorded at the time of each hydrometer reading.
6. Grain size distribution curves and sediment volume data were used to evaluate the relative effectiveness of the various chemical additives on the degree of flocculation and the sedimentation rate of suspended solids.

PRESENTATION OF RESULTS

A total of 114 individual flocculation-sedimentation tests were conducted with the chemical additives listed in Table 5-1 on Samples C2DM, C3TO, C5CO, C22TO, and C27MM. Twenty-two chemical additives were used with the C22TO material, and fourteen were used with each of the other materials.

Table 5-1. Summary of Chemical Additives Studied

Calcium oxide, lime (CaO)
Sodium chloride ($NaCl$)
Calcium chloride ($CaCl_2$)
Calcium carbonate ($CaCO_3$)
Sodium hydroxide ($NaOH$)
Potassium hydroxide (KOH)
Sulfuric acid (H_2SO_4)
Nitric acid (HNO_3)
Hydrochloric acid (HCl)
Phosphoric acid (H_3PO_4)
Acetic acid (CH_3COOH)
Aluminum Sulfate ($Al_2(SO_4)_3 \cdot 18H_2O$)
Sodium hexametaphosphate
Calgon ($Na_3(PO_3)_6$)
o-nitrophenol ($NO_2C_6H_4OH$)
p-nitrophenol ($NO_2C_6H_4OH$)
Tri-nitrophenol ($(NO_2)_3C_6H_2OH$)
p-benzoquinone ($C_6H_4O_2$)
Pyrogallol (1,2,3, trihydroxy benzone)($C_6H_3(OH)_3$)
Certified resorcinol ($C_6H_4(OH)_2$)
Lab grade resorcinol ($C_6H_4(OH)_2$)
Polyvinyl alcohol ($(CH_2CHOH)_n$)
Krilium (Sodium salt of
hydrolyzed polyacrylonitrite)

The number of tests that could be conducted at any one time was limited by equipment availability. In a given test series one blank sample was tested in conjunction with samples of the same material treated with various additives. Due to difficulties in obtaining representative samples, and due to chemical and biological changes during storage, the properties of a particular material were not necessarily the same in different test series. Figure 5-1a shows the variation in the grain size distribution curves for untreated C22TO material, as obtained in different test series; the untreated C2DM material manifested similar variations. Figure 5-1b indicates much less variation between series for the grain size distribution curves of the untreated C3TO material. The untreated C5CO and C27MM materials also had quite similar grain size distribution curves for each series of tests.

Grain size distribution curves and sediment volume versus time curves were plotted for each of the 114 tests. Figure 5-1c shows a typical set of particle size distribution curves for C2DM material that was untreated and treated with a chemical flocculant and a chemical dispersant; although these results are generally representative of those obtained in other tests on other materials, the distributions varied considerably, depending on the material and chemical tested. For an effective flocculant the grain size distribution curve lies below that for the untreated material at the smaller particle sizes (less than about 0.005 mm). In the intermediate particle size range the curve for the treated material lies above that for the untreated material; this is due to the lower density of the flocs relative to the solids particles. Furthermore, once the boundary of the sediment intersects the bulb of the hydrometer, the resulting curve may not accurately define the particle size; however, this curve is still useful in an average sense.

One means of evaluating the effectiveness of a particular chemical in flocculating a dredging material is to calculate the "percentage of

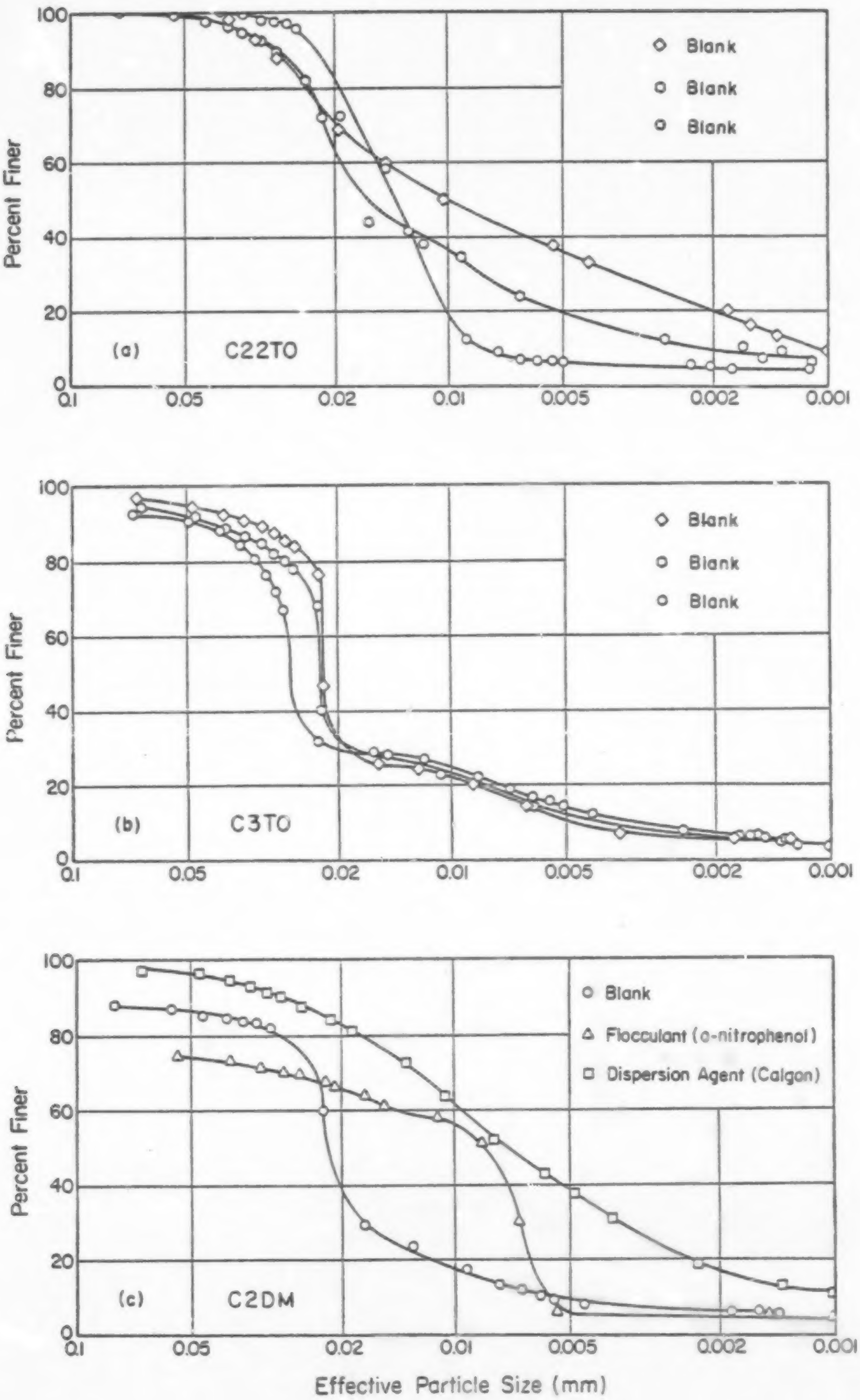


Figure 5-1. Effective Particle Size Distribution Curves

flocculation" at various particle sizes. The percentage of flocculation is defined as:

$$\% \text{ Floc} = \frac{U - T}{U} \quad , \qquad (5\text{-}1)$$

where U equals the percent finer than particle size D for the untreated soil and T represent the percent finer than particle size D for the treated soil Tables 5-2 through 5-6 summarize the percentage of flocculation at several particle sizes for the chemically treated dredging materials. The times given at the top of the table are the elapsed times at which the specified particle sizes were determined in the hydrometer test, and they give an indication of the time required for sedimentation. Dashes in the table indicate negative values of the "percentage of flocculation"; this is caused by the fact that the flocs have a lower density than individual particles and by the inherent inaccuracy in the hydrometer determination.

The results show that a given chemical additive does not work equally well for all of the materials. Of the inorganic chemicals, calcium oxide (lime) appears to be an effective flocculant for each of the dredging materials, but it was much less effective for some (for example, C22TO) than for others. Sodium chloride performed quite well with C22TO, C27MM, and C3TO, but it was ineffective with the other materials. Calcium chloride was effective with C27MM and C3TO only. Calcium carbonate was effective with C3TO, C27MM, and C22TO. Aluminum sulfate was used only with C22TO and was an effective flocculant for that material.

Of the organic chemicals the nitrophenol appears to be the most effective flocculant. Tri-nitrophenol is more effective for C27MM and C22TO, whereas o-nitrophenol and p-nitrophenol are most effective for C2DM and C3TO, and nearly as effective for C27MM. None of the nitrophenols were effective for C3CO. Of the other organic chemicals only resorcinol showed any effectiveness, and then only with C27MM. Inorganic acids and bases

Table 5-2

Percentage of Flocculation for C2DM

Approximate Elapsed Time (minutes)	20	40	150	600	2580
Particle Size (mm)	0.01	0.008	0.004	0.002	0.001
4% calcium oxide (lime)	—	—	13.9	3.6	9.5
2% sodium chloride	—	—	—	—	—
2% calcium chloride	—	—	8.3	3.6	2.4
4% calcium carbonate	0	—	—	—	—
10% sodium hexameta-phosphate (Calgon)	—	—	—	—	—
2% o-nitrophenol	—	—	32.4	25.0	17.8
2% p-nitrophenol	—	—	42.3	29.1	14.3
2% tri-nitrophenol	—	—	—	—	—
2% p-benzoquinone	.0	0	0	0	0
2% pyrogallol	—	—	—	—	—
2% certified resorcinol	0	—	—	—	0
2% lab grade resorcinol	0	—	—	—	0
7 millimole/m.e. o-nitrophenol					
7 millimole/m.e. p-nitrophenol					
7 millimole/m.e. tri-nitrophenol	—	—	—	—	—
7 millimole/m.e. p-benzoquinone					
7 millimole/m.e. pyrogallol					
7 millimole/m.e. certified resorcinol					
7 millimole/m.e. lab grade resorcinol					
0.2% polyvinyl alcohol	30.0	7.1		—	0
0.2% sodium salt of hydrolyzed polyacrylonitrite (Krilium)	—	—	—	—	—
4.2 millimole/m.e. sodium hydroxide					
4.2 millimole/m.e. potassium hydroxide					
2.1 millimole/m.e. sulfuric acid					
4.2 millimole/m.e. nitric acid					
4.2 millimole/m.e. hydrochloric acid					
1.4 millimole/m.e. phosphoric acid					
4.2 millimole/m.e. acetic acid					
0.7 millimole/m.e. aluminum sulfate					

Table 5-3

Percentage of Flocculation for C3TO

Approximate Elapsed Time (minutes)	20	40	150	600	2580
Particle Size (mm)	0.01	0.008	0.004	0.002	0.001
4% calcium oxide (lime)	—	—	13.9	3.6	9.5
2% sodium chloride	—	—	—	—	—
2% calcium chloride	—	—	8.3	3.6	2.4
4% calcium carbonate	0	—	—	—	—
10% sodium hexameta-phosphate (Calgon)	—	—	—	—	—
2% o-nitrophenol	—	—	32.4	25.0	17.8
2% p-nitrophenol	—	—	42.3	29.1	14.3
2% tri-nitrophenol	—	—	—	—	—
2% p-benzoquinone	.0	0	0	0	0
2% pyrogallol	—	—	—	—	—
2% certified resorcinol	0	—	—	—	0
2% lab grade resorcinol	0	—	—	—	0
7 millimole/m.e. o-nitrophenol					
7 millimole/m.e. p-nitrophenol					
7 millimole/m.e. tri-nitrophenol	—	—	—	—	—
7 millimole/m.e. p-benzoquinone					
7 millimole/m.e. pyrogallol					
7 millimole/m.e. certified resorcinol					
7 millimole/m.e. lab grade resorcinol					
0.2% polyvinyl alcohol	30.0	7.1	—	—	0
0.2% sodium salt of hydrolyzed polyacrylonitrite (Krilium)	—	—	—	—	—
4.2 millimole/m.e. sodium hydroxide					
4.2 millimole/m.e. potassium hydroxide					
2.1 millimole/m.e. sulfuric acid					
4.2 millimole/m.e. nitric acid					
4.2 millimole/m.e. hydrochloric acid					
1.4 millimole/m.e. phosphoric acid					
4.2 millimole/m.e. acetic acid					
0.7 millimole/m.e. aluminum sulfate					

Table 5-4

Percentage of Flocculation for C5CO

Approximate Elapsed Time (minutes)	20	40	150	600	2580
Particle Size (mm)	0.01	0.008	0.004	0.002	0.001
4% calcium oxide (lime)	—	71.0	12.8	14.0	16.7
2% sodium chloride	1.2	2.2	—	—	—
2% calcium chloride	—	—	0	0	0
4% calcium carbonate	31.0	35.8	—	—	—
10% sodium hexameta-phosphate (Calgon)	—	—	—	—	—
2% o-nitrophenol	—	4.7	—	—	—
2% p-nitrophenol	—	—	—	—	—
2% tri-nitrophenol	—	20.0	—	—	—
2% p-benroquinone	—	8.7	—	—	—
2% pyrogallol	45.5	48.4	—	—	—
2% certified resorcinol	—	15.7	0	0	0
2% lab grade resorcinol	—	6.7	0	0	0
7 millimole/m.e. o-nitrophenol					
7 millimole/m.e. p-nitrophenol					
7 millimole/m.e. tri-nitrophenol	35.4	31.6	—	—	—
7 millimole/m.e. p-benzoquinone					
7 millimole/m.e. pyrogallol					
7 millimole/m.e. certified resorcinol					
7 millimole/m.e. lab grade resorcinol					
0.2% polyvinyl alcohol	12.1	42.0	0	0	0
0.2% sodium salt of hydrolyzed polyacrylonitrite (Krilium)	75.4	76.2	—	—	—
4.2 millimole/m.e. sodium hydroxide					
4.2 millimole/m.e. potassium hydroxide					
2.1 millimole/m.e. sulfuric acid					
4.2 millimole/m.e. nitric acid					
4.2 millimole/m.e. hydrochloric acid					
1.4 millimole/m.e. phosphoric acid					
4.2 millimole/m.e. acetic acid					
0.7 millimole/m.e. aluminum sulfate					

Table 5-5

Percentage of Flocculation for C22TO

Approximate Elapsed Time (minutes)	20	40	150	600	2580
Particle Size (mm)	0.01	0.008	0.004	0.002	0.001
4% calcium oxide (lime)	—	—	—	19.6	7.7
2% sodium chloride	21.5	23.3	11.0	0	0
2% calcium chloride	—	—	—	—	—
4% calcium carbonate	7.7	8.0	23.2	16.7	24.3
10% sodium hexameta-phosphate (Calgon)	—	—	—	—	—
2% o-nitrophenol	—	—	—	—	39.4
2% p-nitrophenol	—	—	—	—	44.7
2% tri-nitrophenol	27.6	46.7	47.5	13.3	21.4
2% p-benzoquinone	—	—	—	—	—
2% pyrogallol	—	—	—	—	—
2% certified resorcinol	—	—	—	—	—
2% lab grade resorcinol	—	—	—	—	—
7 millimole/m.e. o-nitrophenol	—	—	—	0	0
7 millimole/m.e. p-nitrophenol	—	—	—	—	—
7 millimole/m.e. tri-nitrophenol	—	—	—	—	—
7 millimole/m.e. p-benzoquinone	—	—	—	—	—
7 millimole/m.e. pyrogallol	—	—	—	—	—
7 millimole/m.e. certified resorcinol	2.5	—	—	—	—
7 millimole/m.e. lab grade resorcinol	3.3	—	—	—	—
0.2% polyvinyl alcohol	0	—	—	—	—
0.2% sodium salt of hydrolyzed polyacrylonitrite (Krilium)	23.5	—	—	—	—
4.2 millimole/m.e. sodium hydroxide	—	—	—	—	—
4.2 millimole/m.e. potassium hydroxide	—	—	—	—	—
2.1 millimole/m.e. sulfuric acid	—	—	50.0	30.0	—
4.2 millimole/m.e. nitric acid	—	—	61.0	37.5	—
4.2 millimole/m.e. hydrochloric acid	—	—	67.2	50.0	—
1.4 millimole/m.e. phosphoric acid	—	—	65.6	55.0	—
4.2 millimole/m.e. acetic acid	—	—	56.3	45.0	—
0.7 millimole/m.e. aluminum sulfate	—	—	46.9	22.5	—

Table 5-6

Percentage of Flocculation for C27MM

Approximate Elapsed Time (minutes) Particle Size (mm)	20 0.01	40 0.008	150 0.004	600 0.002	2580 0.001
4% calcium oxide (lime)	—	—	39.2	37.0	8.8
2% sodium chloride	29.3	34.6	15.0	22.0	0
2% calcium chloride	—	55.9	38.3	36.2	6.3
4% calcium carbonate	18.9	20.0	13.1	15.4	8.4
10% sodium hexameta-phosphate (Calgon)	—	—	—	—	—
2% o-nitrophenol	37.4	60.9	62.5	58.5	50.5
2% p-nitrophenol	0	43.1	64.4	65.0	59.0
2% tri-nitrophenol	55.5	60.2	62.5	61.0	61.1
2% p-benzoquinone	9.9	13.3	9.4	0	0
2% pyrogallol	—	—	—	—	—
2% certified resorcinol	19.7	22.2	25.6	23.6	23.2
2% lab grade resorcinol	23.0	21.8	26.3	22.8	20.0
7 millimole/m.e. o-nitrophenol	—	35.0	35.0	35.4	6.3
7 millimole/m.g. p-nitrophenol	—	1.3	15.0	10.3	2.5
7 millimole/m.e. tri-nitrophenol	—	—	—	—	—
7 millimole/m.e. p-benzoquinone	—	—	—	—	—
7 millimole/m.e. pyrogallol	—	—	—	—	—
7 millimole/m.e. certified resorcinol	—	—	—	—	—
7 millimole/m.e. lab grade resorcinol	—	—	—	—	—
0.2% polyvinyl alcohol	—	—	—	—	—
0.2% sodium salt of hydrolyzed polyacrylonitrite (Krilium)	—	—	—	—	—
4.2 millimole/m.e. sodium hydroxide					
4.2 millimole/m.e. potassium hydroxide					
2.1 millimole/m.e. sulfuric acid					
4.2 millimole/m.e. nitric acid					
4.2 millimole/m.e. hydrochloric acid					
1.4 millimole/m.e. phosphoric acid					
4.2 millimole/m.e. acetic acid					
0.7 millimole/m.e. aluminum sulfate					

were used as treatments for C22TO only, and the acids were all effective flocculants for that material.

Table 5-7 illustrates the effect of the various chemical additives on the median grain size (particle size for which 50% of the particles in the material are smaller) for each of the dredging materials. Results within a series of tests should be compared with the results for the blank specimen, which are presented above the results for the chemicals used in that series. The median grain size does not give a good indication of the flocculation effectiveness, since in most cases it is smaller than for untreated materials for both flocculants and dispersants. The median grain size of flocculated materials depends on the predominant floc size, which may be less than the median grain size of the untreated material.

Another means for evaluating the flocculation effectiveness of chemical additives is by comparing sediment volumes as a function of time for treated and untreated materials. Figure 5-2 shows typical results for an untreated material and for the same material treated with a flocculant (lime) and a dispersant (Calgon). Within a few minutes after starting a flocculation-sedimentation test, a distinct boundary usually developed between the flocculated material and the overlying relatively clear suspension for the untreated and flocculant-treated materials. The boundary lowers with time as the coagulated material accumulates and the sediment volume decreases. Materials treated with a dispersing agent develop a small initial sediment after about 10 to 15 minutes; this sediment consists of coarser particles, and it slowly increases in volume with time; the suspension portion of the material is much less clear than that for a flocculant-treated material.

Tables 5-8 through 5-12 give the sediment volumes at various times during the tests for all of the tests performed. In general, the chemical

Table 5-7

Median Effective Grain Size

	Median Grain Size, D_{50} (mm)				
Sample Number	C2BM	C3TO	C5CO	C22TO	C27MH
Blank	0.0205	0.0177	0.0100	0.0130	0.0220
4% calcium oxide (lime)	0.0091	0.0059	0.0096	0.0047	0.0102
2% sodium chloride	0.0112	0.0205	0.0069	0.0145	0.0220
2% calcium chloride	0.0096	0.0085	0.0087	0.0090	0.0113
4% calcium carbonate	0.0127	0.0221	0.0124	0.0164	0.0205
10% sodium hexameta-phosphate (Calgon)	0.0076	0.0081	0.0115	0.0012	0.0070
Blank	0.0205	0.0218	0.0067	0.0130	0.0248
2% o-nitrophenol	0.0083	0.0143	0.0074	0.0103	0.0139
2% p-nitrophenol	0.0088	0.0128	0.0063	0.0063	0.0125
2% tri-nitrophenol	0.0105	0.0097	0.0084	0.0125	0.0160
2% p-benzoquinone	0.0160	0.0140	0.0075	0.0162	0.0200
2% pyrogallol	0.0120	0.0160	0.0136	0.0158	0.0255
2% certified resorcinol	0.0188	0.0225	0.0079	0.0203	0.0280
2% lab grade resorcinol	0.0189	0.0224	0.0074	0.0200	0.0250
0.2% polyvinyl alcohol	0.0200	0.0220	0.0092	0.0178	0.0224
0.2% sodium salt of hydrolyzed polyacrylonitrite (Krilium)	0.0366	0.0224	0.0278	0.0195	0.0320
Blank	0.0120	0.0224	0.0071	0.0180	0.0220
7 millimole/m.e. o-nitrophenol				0.0048	0.0139
7 millimole/m.e. p-nitrophenol				0.0043	0.0117
7 millimole/m.e. tri-nitrophenol	0.0063	0.0054	0.0085	0.0057	0.0100
7 millimole/m.e. p-benzoquinone				0.0083	0.0195
7 millimole/m.e. pyrogallol				0.0138	0.0230
7 millimole/m.e. certified resorcinol				0.0180	0.0278
7 millimole/m.e. lab grade resorcinol				0.0210	0.0243
Blank				0.0103	
4.2 millimole/m.e. sodium hydroxide				0.0022	
4.2 millimole/m.e. potassium hydroxide				0.0049	
2.1 millimole/m.e. sulfuric acid				0.0074	
4.2 millimole/m.e. nitric acid				0.0075	
4.2 millimole/m.e. hydrochloric acid				0.0068	
1.4 millimole/m.e. phosphoric acid				0.0065	
4.2 millimole/m.e. acetic acid				0.0071	
0.7 millimole/m.e. aluminum sulfate				0.0059	

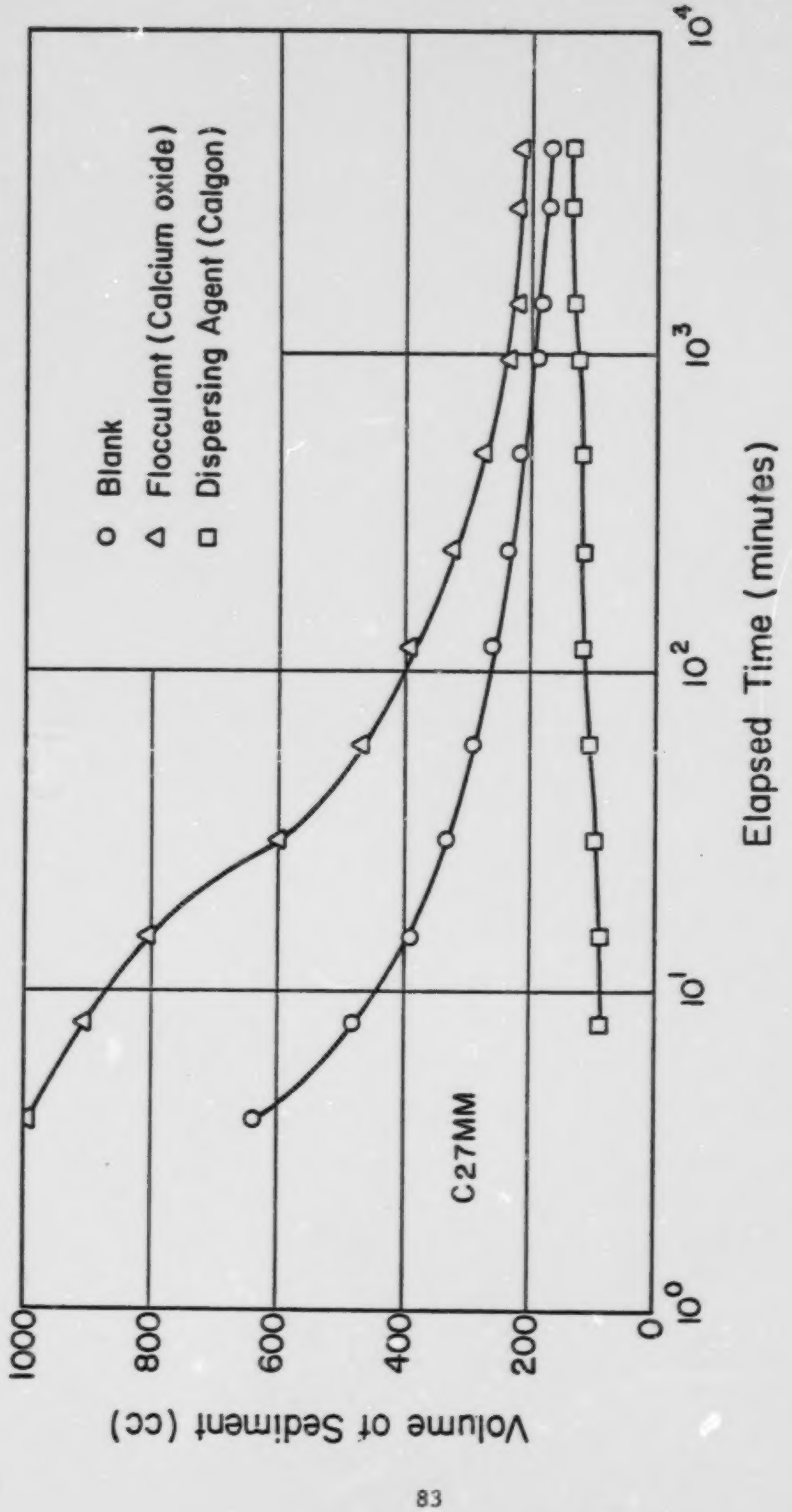


Figure 5-2. Sediment Volume versus Time

Table 5-8

Sediment Volume of C2DM

	Sediment Volume (cm^3)											
Elapsed Time (minutes)	4	8	15	30	60	120	240	480	960	1440	2880	4320
Blank	—	—	245	238	243	235	215	195	173	162	151	148
4% calcium oxide (lime)	865	632	746	568	404	341	296	251	216	212	205	203
2% sodium chloride	812	720	600	450	378	332	295	255	218	200	183	172
2% calcium chloride	900	847	721	586	406	280	235	194	157	148	137	135
4% calcium carbonate	829	700	563	420	365	327	296	261	228	212	187	181
10% sodium hexameta-phosphate (Calgon)	62	66	88	185	263	286	310	333	321	310	285	269
Blank	--	--	244	237	242	234	214	194	172	161	150	147
2% o-nitrophenol	680	626	566	451	302	266	228	191	162	158	153	152
2% p-nitrophenol	697	640	575	455	316	277	239	200	168	162	153	151
2% tri-nitrophenol	894	800	673	515	436	383	340	299	262	242	219	210
2% p-benzoquinone	—	338	256	228	222	211	200	188	176	168	155	151
2% pyrogallol	—	—	—	—	128	162	173	183	186	176	160	148
2% certified resorcinol	--	310	241	213	211	204	197	190	180	173	160	153
2% lab grade resorcinol	—	321	246	211	206	202	200	197	180	173	160	154
0.2% polyvinyl alcohol	426	336	261	219	195	183	173	164	154	148	140	136
0.2% sodium salt of hydrolyzed polyacrylonitrite (Krilium)	163	138	122	109	101	97	91	88	85	85	85	84
Blank	842	720	599	447	374	331	295	260	225	210	199	197
7 millimole/m.e. o-nitrophenol												
7 millimole/m.e. p-nitrophenol												
7 millimole/m.e. tri-nitrophenol	950	930	900	797	600	467	397	340	287	263	239	228
7 millimole/m.e. p-benzoquinone												
7 millimole/m.e. pyrogallol												
7 millimole/m.e. certified resorcinol												
7 millimole/m.e. lab grade resorcinol												

Table 5-9

Sediment Volume of C3TO

	Sediment Volume (cm^3)											
Elapsed Time (minutes)	4	8	15	30	60	120	240	480	960	1440	2880	4320
Blank	—	248	206	195	194	203	200	197	195	191	178	170
4% calcium oxide (lime)	720	704	687	631	539	360	274	220	170	164	162	161
2% sodium chloride	618	483	367	297	282	260	235	209	185	172	146	131
2% calcium chloride	933	863	800	640	424	336	286	234	187	162	161	160
4% calcium carbonate	539	428	331	278	275	265	253	240	220	210	179	164
10% sodium hexameta-phosphate (Calgon)	—	701	619	551	440	378	324	274	254	243	225	212
Blank	—	410	318	296	296	290	280	259	239	221	188	170
2% o-nitrophenol	858	700	547	429	370	328	289	252	221	209	197	192
2% p-nitrophenol	830	720	590	450	381	332	206	250	218	202	186	180
2% tri-nitrophenol	822	737	649	499	410	357	308	260	222	204	186	181
2% p-benzoquinone	—	—	288	294	286	274	259	232	208	195	178	173
2% pyrogallol	—	139	135	133	147	206	252	261	261	248	230	217
2% certified resorcinol	590	409	325	297	282	273	253	237	221	209	186	176
2% lab grade resorcinol	565	391	317	294	271	269	252	236	220	208	185	175
0.2% polyvinyl alcohol	579	400	317	289	276	261	245	228	210	195	168	155
0.2% sodium salt of hydrolyzed polyacrylonitrite (Krilium)	558	430	368	327	299	270	241	215	195	183	163	156
Blank	546	348	273	248	250	246	244	240	225	216	193	174
7 millimole/m.e. o-nitrophenol												
7 millimole/m.e. p-nitrophenol												
7 millimole/m.e. tri-nitrophenol	830	807	781	730	617	434	341	267	239	214	192	184
7 millimole/m.e. p-benzoquinone												
7 millimole/m.e. pyrogallol												
7 millimole/m.e. certified resorcinol												
7 millimole/m.e. lab grade resorcinol												

Table 5-10

Sediment Volume of C5CO

	Sediment Volume (cm^3)											
Elapsed Time (minutes)	4	8	15	30	60	120	240	480	960	1440	2880	4320
Blank	—	824	709	570	384	299	258	216	188	177	160	155
4% calcium oxide (lime)	—	686	582	411	329	270	235	199	176	173	169	158
2% sodium chloride	676	648	612	550	431	280	239	199	171	158	145	140
2% calcium chloride	—	884	782	637	417	329	278	228	192	183	164	160
4% calcium carbonate	678	604	528	447	326	253	221	192	167	156	144	140
10% sodium hexameta-phosphate (Calgon)	—	—	—	—	246	284	270	255	230	215	191	181
Blank	—	578	552	496	395	284	244	213	180	165	150	145
2% o-nitrophenol	575	550	521	443	325	276	240	210	181	172	163	160
2% p-nitrophenol	576	564	545	486	387	299	260	225	194	180	164	159
2% tri-nitrophenol	650	617	565	477	346	297	261	224	200	188	176	172
2% p-benzoquinone	595	571	535	461	351	281	248	218	191	180	164	157
2% pyrogallol	—	—	—	—	—	160	147	137	128	123	123	122
2% certified resorcinol	602	577	540	456	347	266	231	210	181	168	153	150
2% lab grade resorcinol	601	580	546	475	368	287	250	221	193	180	163	158
0.2% polyvinyl alcohol	590	555	506	423	316	256	226	201	178	166	149	140
0.2% sodium salt of hydrolyzed polyacrylonitrite (Krilium)	360	297	253	218	192	170	156	143	131	128	128	129
Blank	640	611	580	526	424	286	248	220	184	179	161	153
7 millimole/m.e. o-nitrophenol												
7 millimole/m.e. p-nitrephenol												
7 millimole/m.e. tri-nitrophenol	—	565	402	332	276	228	198	183	175	174	173	173
7 millimole/m.e. p-benzoquinone												
7 millimole/m.e. pyrogallol												
7 millimole/m.e. certified resorcinol												
7 millimole/m.e. lab grade resorcinol												

Table 5-11

Sediment Volume of C22TO

Elapsed Time (minutes)	Sediment Volume (cm^3)											
	4	8	15	30	60	120	240	480	960	1440	2880	4320
Blank	—	711	584	449	347	298	263	230	200	188	172	167
4% calcium oxide (lime)	—	808	781	742	648	480	384	288	240	221	188	174
2% sodium chloride	—	—	422	322	316	297	276	256	229	211	182	168
2% calcium chloride	—	809	746	642	433	344	295	244	210	193	176	170
4% calcium carbonate	—	470	370	297	308	300	290	278	251	236	207	190
10% sodium hexameta-phosphate (Calgon)	25	26	25	30	34	35	35	36	37	39	41	42
Blank	—	711	584	449	347	298	263	230	200	188	172	167
2% o-nitrophenol	662	578	503	405	354	324	293	265	235	220	199	191
2% p-nitrophenol	701	645	585	476	386	348	310	274	237	217	193	182
2% tri-nitrophenol	831	680	551	455	389	356	326	297	263	244	218	203
2% p-benzoquinone	662	352	293	264	247	236	227	217	206	200	188	180
2% pyrogallol	702	236	209	202	212	224	236	247	250	237	207	185
2% certified resorcinol	439	298	256	231	216	220	225	230	230	224	209	201
2% lab grade resorcinol	441	311	278	255	244	235	228	221	211	204	185	170
0.2% polyvinyl alcohol	530	427	337	293	274	258	242	228	210	199	176	168
0.2% sodium salt of hydrolyzed polyacrylonitrite (Krilium)	472	384	345	313	286	261	237	214	192	181	166	160
Blank	—	363	285	255	275	274	273	262	254	236	213	195
7 millimole/m.e. o-nitrophenol	—	727	709	673	579	422	361	319	279	258	229	214
7 millimole/m.e. p-nitrophenol	—	718	709	682	614	486	354	310	267	240	204	189
7 millimole/m.e. tri-nitrophenol	—	794	765	697	550	411	356	308	260	232	212	203
7 millimole/m.e. p-benzoquinone	—	—	—	—	244	251	237	223	209	201	187	180
7 millimole/m.e. pyrogallol	—	—	512	410	403	401	383	359	331	313	282	262
7 millimole/m.e. certified resorcinol	348	282	232	213	207	203	203	204	203	199	191	186
7 millimole/m.e. lab grade resorcinol	632	500	386	326	306	288	270	250	231	220	201	190
Blank	—	122	130	133	141	146	165	186	207	216	222	212
4.2 millimole/m.e. sodium hydroxide	—	20	21	24	27	29	33	38	43	46	53	56
4.2 millimole/m.e. potassium hydroxide	—	40	43	64	86	113	129	143	155	157	156	156
2.1 millimole/m.e. sulfuric acid	975	950	850	714	522	370	311	260	218	204	189	182
4.2 millimole/m.e. nitric acid	970	940	842	680	492	367	304	258	215	195	187	177
4.2 millimole/m.e. hydrochloric acid	985	965	883	770	590	409	340	290	244	223	203	195
1.4 millimole/m.e. phosphoric acid	985	955	880	800	603	420	362	311	267	253	238	236
4.2 millimole/m.e. acetic acid	953	930	893	763	556	410	335	288	245	225	201	198
0.7 millimole/m.e. aluminum sulfate	990	978	934	820	650	480	416	353	300	283	270	265

Table 5-12

Sediment Volume of C27MM

	Sediment Volume (cm^3)											
Elapsed Time (minutes)	4	8	15	30	60	120	240	480	960	1440	2880	4320
Blank	636	479	388	332	291	260	237	218	192	182	171	170
4% calcium oxide (lime)	991	904	803	597	464	387	326	276	237	220	219	214
2% sodium chloride	687	522	406	337	305	272	240	211	191	180	164	157
2% calcium chloride	980	874	745	562	456	382	328	275	232	219	196	184
4% calcium carbonate	596	439	355	304	280	253	227	204	187	177	168	161
10% sodium hexameta-phosphate (Calgon)	—	88	88	96	106	113	114	116	122	130	136	137
Blank	—	360	293	259	234	213	192	180	170	165	157	153
2% o-nitrophenol	790	685	549	433	361	306	260	227	206	198	188	185
2% p-nitrophenol	767	670	540	437	370	317	274	240	215	203	188	182
2% tri-nitrophenol	765	666	437	400	350	305	276	249	224	212	197	188
2% p-benzoquinone	—	498	400	341	302	268	236	212	195	189	182	181
2% pyrogallol	301	252	216	199	188	176	168	166	167	167	166	163
2% certified resorcinol	610	440	324	287	253	234	211	196	184	180	174	172
2% lab grade resorcinol	585	433	322	283	253	228	203	188	176	170	165	160
0.2% polyvinyl alcohol	—	331	290	257	236	214	198	181	168	163	158	157
0.2% sodium salt of hydrolyzed polyacrylonitrite (Krilium)	446	315	284	244	215	193	176	165	154	153	152	151
Blank	636	479	388	332	291	260	237	218	192	182	171	170
7 millimole/m.e. o-nitrophenol	968	832	659	506	419	346	302	255	230	225	217	213
7 millimole/m.e. p-nitrophenol	995	873	734	549	466	369	313	266	223	211	191	187
7 millimole/m.e. tri-nitrophenol	—	950	814	600	475	390	328	283	245	235	220	214
7 millimole/m.e. p-benzoquinone	—	—	—	296	276	245	223	202	192	190	186	183
7 millimole/m.e. pyrogallol	—	446	334	282	252	223	204	188	174	166	159	157
7 millimole/m.e. certified resorcinol	610	462	375	320	283	246	221	200	184	180	172	170
7 millimole/m.e. lab grade resorcinol	617	455	366	310	279	248	217	194	179	173	170	168

additives that were found to be effective flocculants (based on the "percentage of flocculation" of fine-grained materials) also give the greater initial sediment volumes, again indicating effective flocculation. In most cases the more effective flocculants also result in larger sediment volumes (relative to the untreated materials) after 3 days of settling although the differences are not always very large.

DISCUSSION

It is generally accepted that a clay soil sediment in a flocculated state has a more open structure and therefore a larger sediment volume than an equal amount of the material in a dispersed state. The results in Tables 5-8 through 5-12 for the dredged materials tested in this study indicate that this is not always true. For example, for four of the five materials the sediment volume after 3 days is larger when treated with a dispersant (Calgon) than when untreated or treated with a flocculating agent. Also, in some cases the final sediment volume was larger for the untreated materials than for the same materials treated with known effective flocculants. In his discussion of the dispersion and flocculation characteristics of kaolinite, Edil (1973) reported that:

> "The decrease in sediment volume with high salt-concentration (2.0M NaCl or 2.0M $CaCl_2$), as compared with the sediment volume at lower concentrations, is believed to be due to the face-to-face aggregation of particles, which yields a particle arrangement termed 'book-house'. ...In the case of Hydrite R, a distilled water suspension had a higher height ratio than those of all salt-flocculated suspensions with both NaCl and $CaCl_2$ as the salt type. Flocculation of suspensions prepared with distilled water is basically due to the low pH."

The pH of the as-sampled materials tested in this study ranged from about 7.4 to 8.0. Although biological and chemical changes during storage may have lowered the pH sufficiently to cause the type of flocculation discussed by Edil (1973) and perhaps account for the occasionally larger final sediment volumes for the untreated materials, this does not explain the relatively large final sediment volumes for the materials treated with a known dispersant (Calgon).

The dredgings used in this study contained a considerable portion of silt and sand size particles. In a dispersed suspension these particles settle first and are then covered by the clay sediment as time progresses. In a flocculated suspension the effective size of many of the flocs may be of the same order of magnitude as the silt particles and, in fact, the flocs may form around the silt particles. However, the effective specific gravity of the flocs is generally less than that of the soil solids, since a certain portion of the water moves with and may be considered as part of the floc. Nevertheless, much of the silt size material settles together with the flocculated clay particles, and the resulting sediment consists of a more homogeneous mixture, which may occupy less volume than the sediment from a dispersed suspension. Therefore, in evaluating the effectiveness of chemical additives in flocculating dredging materials, the final sediment volume should not be used as a criterion; rather, the initial flocculation rate and the clarity of the supernatant suspension may constitute more reliable criteria. Tables 5-8 through 5-12 give an indication of the effectiveness of initial flocculation (that is, greater initial sediment volumes indicate more effective flocculation), and Table 5-13 summarizes visual observations of the color and clarity of the supernatant for each combination of dredged material and chemical additive tested.

The other criterion suggested for flocculation effectiveness was the "percentage of flocculation" of fine-grained particles. When flocs form in a soil suspension, the effective specific gravity of the flocs is less than that of the soil solids, as mentioned earlier; accordingly, such flocs

Table 5-13

Color and Cloudiness of Dredged Material Supernatants

Chemical Additive		C2DM	C3TO	C5CO	C22TO	C27MH
Calcium oxide, lime CaO		Colorless Clear	Colorless Clear	Colorless Clear	Colorless Clear	Colorless Clear
Sodium chloride $NaCl$		Light gray Cloudy	Light gray Cloudy	Gray Cloudy	Light gray Cloudy	Light gray Cloudy
Calcium chloride $CaCl_2$		Colorless Clear	Colorless Clear	Colorless Clear	Colorless Clear	Colorless Clear
Calcium carbonate $CaCO_3$		Light grey Cloudy	Light gray Cloudy	Gray Cloudy	Light gray Cloudy	Light gray Cloudy
Sodium hydroxide $NaOH$					Dark gray Cloudy	
Potassium hydroxide KOH					Dark gray Cloudy	
Sulfuric acid H_2SO_4					Light brown Cloudy	
Nitric acid HNO_3					Light brown Cloudy	
Hydrochloric acid HCl					Light brown Cloudy	
Phosphoric acid H_3PO_4					Light brown Cloudy	
Acetic acid CH_3COOH					Light brown Cloudy	
Aluminum Sulfate $Al_2(SO_4)_3 \cdot 18H_2O$					Light brown Cloudy	
Sodium hexametaphosphate,calgon $Na_3(PO_3)_6$		Dark gray Cloudy	Dark gray Cloudy	Black Cloudy	Dark gray Cloudy	Dark gray Cloudy
o-nitrophenol $NO_2C_6H_4OH$	2% of solids	Pink Clear	Yellow pink Clear	Dark yellow pink Clear	Yellow pink Clear	Yellow pink Clear
	7 mmole/m.e.				Dark yellow pink Clear	Dark yellow pink Clear
p-nitrophenol $NO_2C_6H_4OH$	2% of solids	Brownish yellow Clear	Yellow Clear	Dark yellow Clear	Yellow Clear	Yellow Clear
	7 mmole/m.e.				Dark yellow Clear	Dark yellow Clear
Tri-nitrophenol $(NO_2)_3C_6H_2OH$	2% of solids	Light pink Clear	Light pink Clear	Dark pink Clear	Light pink Clear	Yellow pink Clear
	7 mmole/m.e.	Dark pink Clear	Dark pink Clear	Dark pink Clear	Dark pink Clear	Dark pink Clear
p-benzoquinone $C_6H_4O_2$	2% of solids	Dark brown Cloudy	Pink grey Cloudy	Dark pink gray Cloudy	Pink gray Cloudy	Pink gray Cloudy
	7 mmole/m.e.				Dark pink grey Cloudy	Dark pink grey Cloudy
Pyrogallol (1,2,3, trihydroxy benzene) $C_6H_3(OH)_3$	2% of solids	Black Cloudy	Black Cloudy	Black Cloudy	Black Cloudy	Black Cloudy
	7 mmole/m.e.				Black Cloudy	Black Cloudy
Certified resorcinol $C_6H_4(OH)_2$	2% of solids	Gray Cloudy	Gray Cloudy	Light gray Cloudy	Gray Cloudy	Gray Cloudy
	7 mmole/m.e.				Light brown gray Cloudy	Light gray Cloudy
Lab grade resorcinol $C_6H_4(OH)_2$	2% of solids	Grey Cloudy	Gray Cloudy	Light gray Cloudy	Gray Cloudy	Gray Cloudy
	7 mmole/m.e.				Light brown gray Cloudy	Light gray Cloudy
Polyvinyl alcohol $(CH_2CHOH)_n$		Gray Cloudy	Light gray Cloudy	Dark gray Cloudy	Light gray Cloudy	Light gray Cloudy
Krilium (Sodium salt of hydrolyzed polyacrylonitrite)		Dark gray Cloudy	Dark gray Cloudy	Dark gray Cloudy	Dark gray Cloudy	Dark gray Cloudy

settle at a slower velocity than solid soil particles of equal size. Using the specific gravity of the soil solids to calculate the effective diameter of the particles results in underestimating the size of the flocs (that is, the flocs will be larger than determined by the standard grain size analysis). Therefore, the actual "percentage of flocculation" of fine-grained particles should be greater than the values given in Tables 5-2 through 5-6. However, these data still give a valid comparison of flocculation effectiveness. Discussed in the following sections is the effectiveness of the various chemical additives used in this investigation for the flocculation of dredging materials.

Calcium Oxide and Calcium Chloride

The flocculation mechanism of these two chemicals is attributed to cation exchange, ionic attraction, and aggregation. In terms of the "percentage of flocculation" (Tables 5-2 through 5-6) calcium oxide was the most effective of the inorganic chemicals in the fine particle size range; calcium chloride was effective with three of the five dredging materials. Tables 5-8 through 5-12 show that the initial sediment volumes were larger for materials treated with these two chemicals than for the same materials treated with the other inorganic chemicals. Table 5-13 shows that the supernatant suspension was colorless and clear for materials treated with calcium oxide and calcium chloride. Because of their effectiveness in flocculating and increasing settling rates and because of their known effectiveness in improving soil strength properties in other applications, calcium oxide and calcium chloride were selected for further investigation.

Calcium Carbonate

Due to the insolubility of calcium carbonate, the cation exchange and ionic attraction mechanisms for flocculation are not as effective as for calcium oxide and calcium chloride. However, the "percentage of flocculation" data shows calcium carbonate to be quite effective with three of the five dredging materials. The initial sediment volumes were generally smaller than for the other two calcium compounds. The supernatant suspension was gray in color and cloudy, indicating less effective flocculation; however, it was judged sufficiently effective to merit further investigation.

Sodium Chloride

The addition of sodium ions to a soil suspension may cause dispersion or flocculation, depending on how many sodium ions were present in the material and how many were added. The test data show that sodium chloride was fairly effective in flocculating two of the five dredging materials. The supernatant suspension was gray in color and cloudy, although the turbidity was reduced from that of the untreated materials.

Aluminum Sulfate

The flocculation mechanisms of aluminum sulfate are essentially coagulation, as described by Sawyer and McCarty (1967). When aluminum sulfate is added to the soil suspension, the molecules dissociate to yield SO_4^{-2}, Al^{+3}, and various aluminum hydrolysis complexes, such as $AL(OH)^{+2}$, $Al(OH)_3$, and $Al(OH)_4^{-1}$. Some of the hydrolysis products also combine to form longer-chain polymeric aluminum hydroxide species of higher charge. The various positive species that are formed may combine with the negatively charged clay particles to neutralize part of the charge on the clay particles, thereby reducing the zeta potential to a value at which agglomeration of the clay particles will occur. During the flocculation period, which usually lasts 20 to 30 minutes, agglomeration of colloidal materials is completed and the soil particles become incorporated in the mass of the precipitated floc. During the sedimentation period the floc settles and leaves a clarified supernatant. However, it is essential that there be a residual alkalinity during the coagulation process to ensure essentially complete precipitation of the coagulating ions.

Aluminum sulfate was used only with Sample C22TO in this study. Although the "percentage of flocculation" and initial sediment volume data show it to be an effective flocculant with that material, the supernatant suspension was brownish-yellow in color and very cloudy after one day of sedimentation; this may have been due to (a) an excessively high concentration of solids in the dredging suspension, (b) an inadequate pH value, or (c) formation of complex sulfate anions which reduced the effectiveness of coagulation. Because of the cloudiness of the supernatant suspension, aluminum sulfate was not considered for further investigation.

Organic Substituted Benzene Ring Compounds

The chemicals investigated from this group include o-nitrophenol, p-nitrophenol, tri-nitrophenol, p-benzoquinone, pyrogallol, and resorcinol. Interlayer adsorption and cross-linking are the basic flocculation mechanisms of this group of compounds. The relative flocculation effectiveness appeared to depend on the number of active groups and the number of unshared electrons. The "percentage of flocculation" data show that the trinitrophenol was effective for three of the materials (C22TO, C3TO, and C27MM). The o-nitrophenol and p-nitrophenol compounds were effective with C27MM, C2DM, and C3TO. None of the nitrophenols were effective with C5CO, according to the "percentage of flocculation" criterion. Initial sediment volume data show that all three nitrophenols were quite effective for all of the dredging materials. Although the supernatant suspension were clear when the nitrophenols were used, the color was yellow-pink, yellow or pink. Because of this visual pollution of the effluent water and questions concerning the toxicity of the effluent, the nitrophenols were not considered for further investigation. Of the remaining four organic substituted benzene ring compounds, only resorcinol displayed any flocculation effectiveness, and this effectiveness was noted for only one dredging material (C27MM). In this case the supernatant suspension remained gray and cloudy. Therefore, resorcinol, p-benzoquinone, and pyrogallol were not considered for further investigation.

Polyvinyl Alcohol and Krilium

Polyvinyl alcohol is a low molecular weight, non-ionic, cold water soluble resin. Krilium is a sodium salt of hydrolysed polyacrylonitrite. Although both materials have been used as soil conditioners in agricultural applications (Kijne, 1967), the data from this study show them to be ineffective as flocculants for the dredging materials.

Acids

Acetic acid and the inorganic phosphoric, sulfuric, nitric, and hydrochloric acids were used to treat the C22TO material. Acids are known to be effective flocculators of fine-grained soil suspensions. As reported by various researchers (Demirel and Davidson, 1960; Michaels and Tausch, 1959), it is believed that the raction products are complex amorphous aluminum salts in the form of gels. Acids also lower the pH or the soil suspension, leading to positive charges on the broken edges of the clay particles and thereby facilitating edge-to-face flocculation of clays. All of the acids were effective in flocculating the C22TO material; phosphoric acid resulted in the greatest "percentage of flocculation" of fines and the largest initial sediment volume. However, after one day of sedimentation the supernatant suspension remained quite cloudy and had a brownish yellow color. Therefore, these acids were not considered for further investigation.

Dispersing Agents

In addition to the possible flocculating chemicals discussed above, the C22TO material was treated with sodium hydroxide and potassium hydroxide, and each of the materials was treated with sodium hexametaphosphate (Calgon); these chemicals are known to be dispersants. The hydroxides supply OH^{-1} ions which increase the pH and reduce the positive charges on the broken edges of the clay particles. Sodium hexametaphosphate provides sodium ions and the complex hexametaphosphate anions tie up the divalent ions that are present in the suspension. The effect is to increase the repulsive forces between the clay particles. Each of these materials was found to be an effective dispersant for these dredging materials.

SUMMARY AND CONCLUSIONS

Flocculation-sedimentation tests were conducted on five different maintenance dredgings treated with various possible chemical flocculants that were selected on the basis of a literature review. The criteria for evaluating the flocculation effectiveness of these additives were the percentage of flocculation of fines, the initial sediment volume, and the color and clarity of the supernatant suspension. Based on an interpretation of the test results in terms of the basic flocculating mechanisms, the flocculation effectiveness of each combination was evaluated and the following conclusions can be advanced.

1. Calcium oxide and calcium chloride were effective flocculants for most of the dredging materials, and the supernatant suspensions were colorless and clear.

2. The o-nitrophenol, p-nitrophenol, and tri-nitrophenol compounds were effective flocculants, but the associated supernatant suspensions, although clear, exhibited a yellow and pink coloration; this visual pollution of the effluent and the possible toxicity of the chemicals suggests these additives are undesirable as flocculants.

3. Acetic acid, phosphoric acid, sulfuric acid, nitric acid, hydrochloric acid, and aluminum sulfate were all effective flocculants, but the supernatant suspensions were cloudy and had a brownish-yellow coloration after a day of settling.

4. Calcium carbonate was quite effective as a flocculant for three of the materials, and sodium chloride was effective with two; however, the supernatant suspensions remained cloudy with both chemicals.

5. The organic chemicals (p-benzoquinone, pyrogallol, polyvinyl alcohol, and Krilium) were not effective flocculants; resorcinol was effective with only one of the dredging materials, but the supernatant suspension remained cloudy.

The most effective flocculants for each of the five dredging materials investigated are summarized in Table 5-14. These chemical additives were selected for further study in sedimentation-leaching tests and an evaluation of their effects on the engineering properties of the resulting sediments. Although calcium carbonate, sodium chloride, and resorcinol may result in cloudier suspensions than calcium oxide and calcium chloride, for practical considerations they will be included in subsequent tests on the engineering properties of the resulting sediments.

Table 5-14

Summary of Chemical Additives found to be Effective Flocculants for Dredged Materials Studied

Dredging Material	Chemical Additive
C2DM	Calcium oxide Calcium chloride
C3TO	Calcium oxide Calcium chloride Calcium carbonate
C5CO	Calcium oxide
C22TO	Calcium oxide Calcium carbonate Sodium chloride
C27MM	Calcium oxide Calcium chloride Calcium carbonate Sodium chloride Resorcinol

Based on the postulated flocculation criteria and the flocculation-dispersion mechanisms for each chemical, sodium hydroxide, potassium hydroxide, and sodium hexametaphosphate (Calgon), are good dispersing agents. Although not specifically shown in the data and the "percentage of flocculation", the initial sediment volume data for visual observation generally indicated that the higher percentages of organic substituted benzene ring compounds (7 millimoles/m.e. -- about 10% of the dry weight of the soil) had a better flocculation effect than did the lower percentages of the same organic compounds. Based on a review of the reports by the Dow Chemical Company, their Purifloc C-31 and Separan 273 polymers are effective flocculants for dredging slurries at concentrations of 0.4 to 20 gm/ℓ; hence, these chemicals are promising flocculants for dredge overflow and weir outflow treatment. A study of the test data obtained from this experimental program in conjunction with the engineering characteristics of the five dredgings investigated indicates that the coarser dredging materials are less responsive to chemical additives.

CHAPTER 6

SEDIMENTATION-LEACHING TESTS

From a soil engineering point of view, whether or not a soil is useful for a desired purpose is judged largely by its shear strength, compressibility, and permeability. From an environmental engineering point of view, the extent to which a disposal process satisfies its intended purpose is juedged to a large degree by the short-term and long-term quality of the surface and groundwater in the surrounding region. The test program reported in this chapter is directed toward studying the effectiveness of chemical stabilization methods in terms of both soil and environmental engineering criteria. To accomplish the objective most directly, the laboratory model should be as similar as possible to the field situation.

When a dredging slurry is discharged into a diked disposal area, the slurry starts to flow toward the overflow weir and simultaneously the solids begin to settle. In general, the following forces act on the solid particles during this stage:

(a) Gravitational forces cause the solid particles to settle.

(b) The horizontal components of the flow drag forces cause the solid particles to move horizontally.

(c) The vertical components of the flow drag forces are derived from downward fluid flow; they are negative if the solid particles settle faster than the downward flow rate.

(d) Physico-chemical forces cause flocculation or dispersion of the clayey particles.

Under normal conditions the first two forces are dominant during the process of sedimentation, after which dewatering and consolidation begin. Several other forces act on the sediment during this stage, and these include:

(a) Seepage forces, which may induce consolidation of the sediment,

(b) Overburden pressures due to the weight of the subsequent deposits of dredged materials,

(c) Physico-chemical forces, such as chemical bond forces, cementation forces, etc, which become prevalent as the clayey particles approach each other.

(d) Capillary forces, which develop as the dredged sediments become unsaturated and the surface tension of the fluid in the pores starts to act, thereby causing additional consolidation.

(e) Forces caused by vegetation as plants begin to grow and their roots draw water from the pores of the sediments.

The last two forces listed above may very well be the major force components causing consolidation of the sediments during the final stages, especially in the top two to three feet.

In general, an actual dredging-disposal process will be more complicated than the situation described above because of (a) channelized flow patterns due to the topography of the area, (b) non-uniformity of the dredged materials, (c) horizontal stratifications and vertical cracking due to repeated drying and wetting processes through dormant periods of the dredging seasons, (d) volcano-like spots distributed over the new drying surface due to the release of gases from the digestion of the lower wet sediments and other related phenomena. Laboratory tests were conducted to study the effects of chemical additives on the sedimentation, consolidation, and stabilization of various dredged materials. As a first step in an attempt to model this problem, a group of simple sedimentation-leaching chambers (3 inches in diameter and 18 inches high with bottom drainage) was designed. In this model the horizontal components of the flow drag forces and the forces caused by vegetation are neglected, the capillary forces can not be fully mobilized, and the overburden pressure is limited. However, an attempt was made to emphasize the physico-chemical forces. The coefficient of permeability was calculated, the shear strength and water content were measured, and the quality of leachate was analyzed chemically. All of these parameters were used as criteria to judge the effectiveness of different chemical stabilizing agents.

SAMPLE PREPARATION AND TEST PROCEDURE

As mentioned in Chapter 5, it was necessary that a blank sample be prepared for each test series. The detailed procedure followed for the sedimentation-leaching test is given below:

(a) Adjust the water content of the material to its initial value at the time of collection.

(b) Based on the dry weight of the solids, add the required amount of chemical additive into the material.

(c) Mix the treated material thoroughly and store in a humid room for 24 hours to allow physico-chemical interactions to take place.

(d) Mix the slurry thoroughly again and place it in a 3-inch diameter sedimentation-leaching chamber to a depth of 18 inches; weigh the treated material again to obtain a check on the water content.

(e) Place the chamber in a humid room and open the valve at the bottom to allow gravity drainage.

(f) Record periodically the height of the water surface and the height of the sediment surface; in most cases for the dredged materials used in this investigation, the major portion of the solid particles settled below the water surface to form a distinct sediment surface within about half an hour after starting drainage.

(g) Weigh separately at each recording time the material remaining in the chamber and the leachate that drained into the bottle to check for evaporation and to obtain data for permeability calculations.

(h) When the surface of the water just reaches the sediment surface, conduct vane shear tests at depth increments of 1 inch; for some dredged materials a very long period of time was required to reach this stage, and in these cases the supernatant liquid was syphoned out when the seepage forces were determined to exert no significant effect (that is, no additional settlement of the sediment was observed).

(i) Continue the leaching process until the quantity of leachate drained from the material shows no significant increase (< 0.01 lbs/week); again, conduct vane shear tests at depth increments of 1 inch to evaluate the effect of capillary tension of the pore fluid on the shear strength of the sediments.

(j) Determine the water content for each corresponding depth at this final stage of the test.

(k) Analyze the chemical composition of the leachate to evaluate the effect of different chemical additives on the pollution potential of the leachates; the detailed test procedure for the chemical analysis of the leachates are given in Chapter 7.

In the case of the sedimentation test alone, the detailed test procedure is described below:

(a) Follow steps 1 through 3 of the procedure for the sedimentation-leaching test.

(b) Mix the slurry thoroughly and transfer it to a 1000 cubic centimeter hydrometer jar, filling it to the designated volume.

(c) Place the jar in a quiescent environment and record periodically the height of the sediment surface.

PRESENTATION OF TEST RESULTS

Twenty-six sedimentation tests and twenty-six parallel sedimentation-leaching tests were conducted. The same initial conditions were used in both tests for a given combination of dredged material and chemical additive. The main purpose of the sedimentation test series was to study the flocculation and sedimentation characteristics of the materials when treated with various percentages of different chemical additives. Although particle settling was due mainly to gravity (that is, no seepage forces), some understanding of the material behavior in the presence of seepage forces can be obtained. All of the data were plotted as volume of sediment versus the logarithm of time, and a procedure similar to the Casagrande method for consolidation tests was used to determine the time and volume of sediment at 100 percent sedimentation; one typical plot is illustrated in Figure 6-1. For easier comparison with the results of the sedimentation-leaching tests, the data in Tables 6-1 and 6-2 are presented in terms of equivalent thickness of sediment, using the initial thickness of the sediment in the sedimentation-leaching test as a base.

With regard to the twenty-six sedimentation-leaching tests, experience with the untreated dredged materials showed that different initial concentrations may lead to different results for the same dredged material. Therefore, in this test program, the initial concentrations of the materials tested in this program was the same as those of the materials as they left the discharge or inflow pipe at the disposal area. After the test was completed, the initial concentration was back-calculated on the basis of the initial weight and volume of the slurry, the specific gravity of the solids, and the final weight and water content of the sediment. The average of the initial and final values was taken as the weight of the solids for the initial concentration, assuming that the weight of solids that leached out was negligible. The data for the positions of the water and sediment surfaces and for the weights of the leachates were plotted versus the logarithm of time.

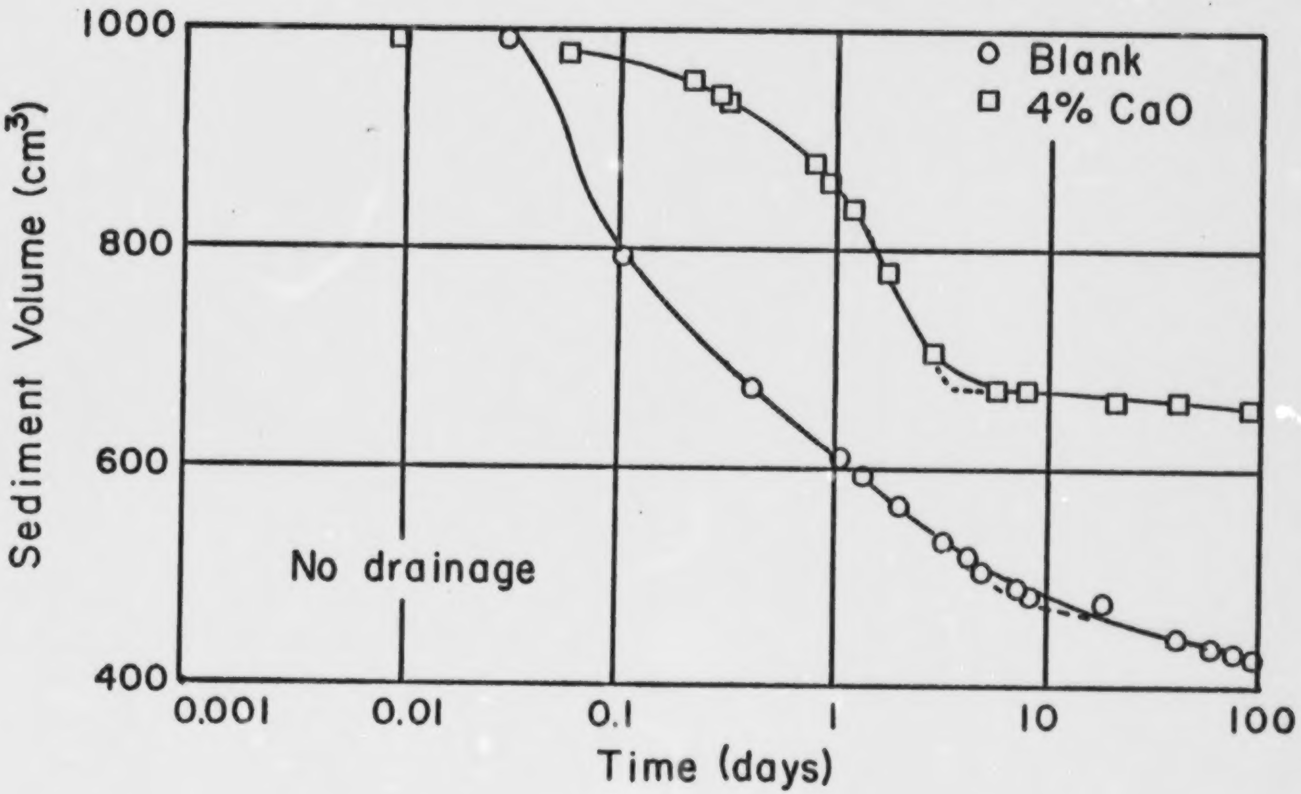


Figure 6-1 Typical Plot of Sedimentation Test Data

Following the same procedure used for the sedimentation tests, the thickness of the sediment and the time for 100 percent consolidation (sedimentation) were found, and typical plots are shown in Figure 6-2. All of the controlling parameters are summarized in Tables 6-1 and 6-2.

The vane shear strength at each inch of depth was measured at the time the water surface coincided with that of the sediment and after leaching was completed. The water content was determined at each inch of depth at the final stage and the average values for all tests are presented in Tables 6-1 and 6-2; the variation of shear strength with depth for all tests was similar to that reported in Figure 10-20 of the report by Krizek, Karadi, and Hummel (1973). The average dry densities given in these tables were calculated from the final weights of the sediments, average water contents, and final volumes of sediments. The average permeabilities given in Tables 6-1 and 6-2 were calculated by the falling head permeability relationship at the time the sediment thickness approached a constant value.

All sedimentation-leaching tests were conducted under gravity forces only to simulate field conditions. However, the shear strengths obtained were relatively low and a meaningful comparison of the effectiveness of the various chemical additives was difficult. Therefore, chemically treated samples of the C22TO material, compacted at optimum water content for the untreated soil, were tested to obtain their unconfined compressive strengths,and the results are also presented in Table 6-1. The solids content, silica, turbidity, pH, and concentrations of metals in the leachates from the blank materials and from most of the sedimentation-leaching samples were determined to obtain an indication

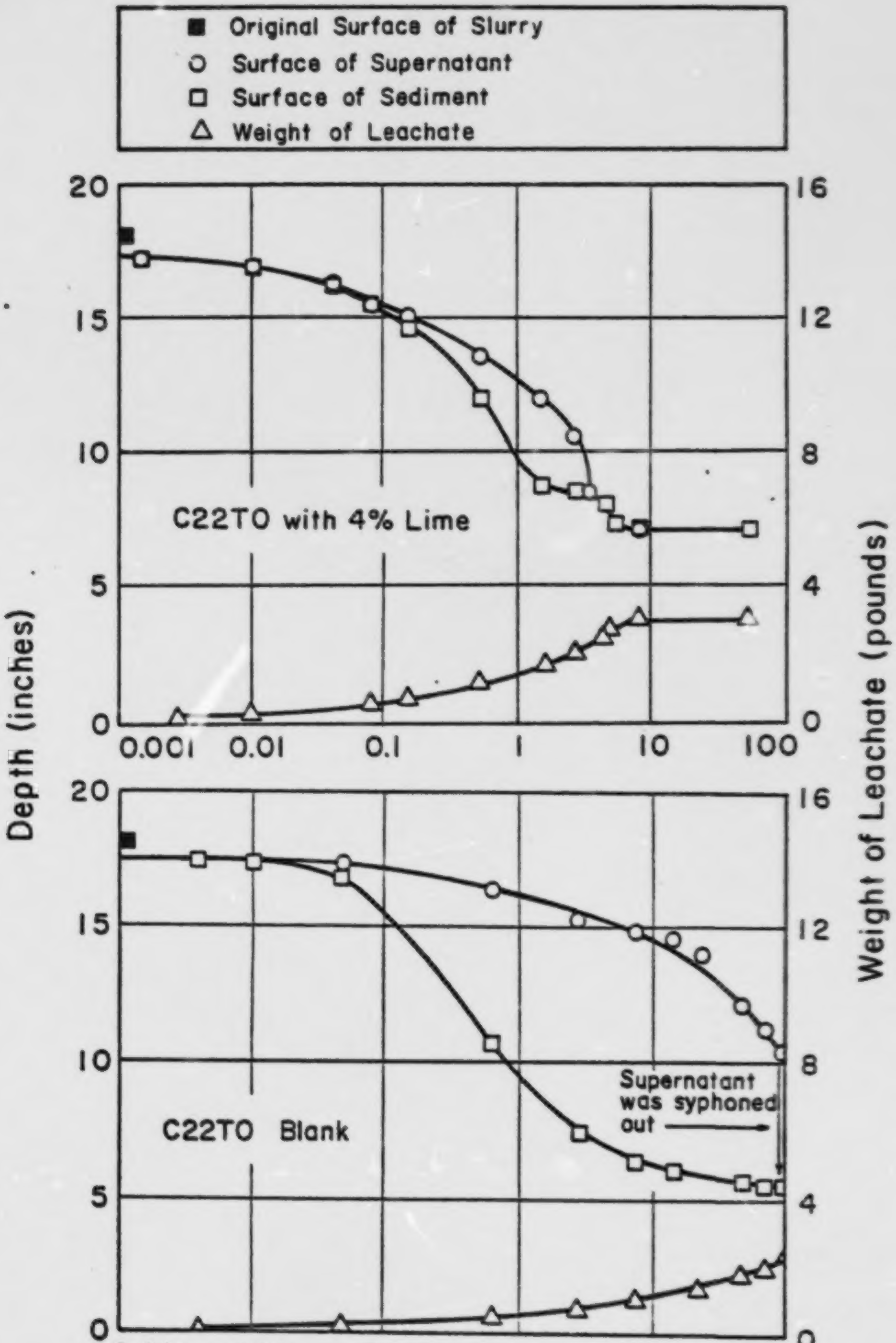


Figure 6-2 Typical Plots of Sedimentation-Leaching Test Data

Table 6-1

Physical and Mechanical Test Results for C22TO

Chemical Added			Blank			CaO			$CaCO_3$			NaCl		
Percentage			I	II	III	2%	4%	6%	2%	4%	6%	2%	3%	4%
Initial Condition	Water Content (%)		470	680	433	490	590	535	479	386	500	400	400	590
	Concentration (gm/ℓ)		197	139	212	189	159	174	194	236	186	228	228	159
Sedimentation Test	Time for 100 Percent Sedimentation (days)		8.0	7.4	7.6	5.5	3.7	2.8	22.5	30.0	37.0	30.0	32.5	19.5
	Thickness of Sediment at t_{100} (inches)		8.5	8.2	8.6	11.3	12.2	12.5	8.9	7.8	8.2	8.9	9.0	9.4
Sedimentation and Leaching Test	Time for 100 Percent Sedimentation (days)		4.5	4.4	4.5	2.0	1.6	1.5	10.6	4.3	6.8	4.2	7.8	10.0
	Thickness of Sediment at t_{100} (inches)		7.9	6.5	6.0	7.5	8.8	8.1	5.6	7.6	7.9	7.3	6.8	5.6
	Time for Supernatant to Leach through Sample (days)				42.0	5.0	3.5	3.4						
	Thickness of Sediment after Finish of Leaching (inches)		6.6	5.0	5.2	6.4	7.2	7.1	4.9	6.3	6.1	6.4	5.5	4.9
	Vertical Shrinkage Due to Capillary Effects (%)		16.5	23.0	13.4	18.0	18.1	13.0	12.5	17.8	22.8	12.4	18.5	11.5
	Average Permeability (10^{-7} cm/sec)		11	6	37	272	411	314	8	5	8	7	5	10
	Final Average Water Content (%)		104	114	100	140	142	133	85	113	96	121	97	96
	Final Average Dry Density (pcf)		36.8	35.3	40.8	32.1	31.8	31.5	44.1	35.0	34.2	32.8	35.3	40.7
	Average Shear Strength (psf)	Without Capillary Effects	40	27	65	22	13	18	61	32	41	31	30	51
		With Capillary Effects	50	38	125	38	27	40	105	60	69	45	51	86
Compacted Sample	Unconfined Compression Strength (pcf) (Ultimate or Value at ϵ=15%)			2980		3560	4810	6200	3020	2490	3260	2200	2440	1940
	Dry Density (pcf)			83.1		83.8	83.3	81.0	85.2	85.8	85.9	86.4	86.7	87.6
	Water Content (%)			34.5		31.6	30.9	30.4	33.2	32.5	32.2	32.2	31.6	31.4

Table 6-2

Physical and Mechanical Test Results for C27MM

Chemical Added			Blank		CaO				$CaCl_2$			Resorcinol			$CaCO_3$	NaCl
Percentage			I	II	2	4	4	6	1	2	4	1	2	3	4	2
Initial Condition	Water Content (%)		1010	812	797	768	750	705	914	743	767	915	919	930	770	705
	Concentration (gm/ℓ)		94	117	118	124	125	133	104	126	124	103	102	101	122	133
Sedimentation Test	Time for 100 Percent Sedimentation (days)		4.5	10.0	1.2	1.1	1.0	1.0	7.7	5.3	5.5	10.0	10.0	8.6	1.3	1.8
	Thickness of Sediment at t_{100} (inches)		6.0	5.8	7.4	8.1	7.9	7.9	6.1	6.5	6.5	6.0	6.1	6.1	6.8	6.8
Sedimentation and Leaching Test	Time for 100 Percent Sedimentation (days)		2.0	5.5	0.5	0.4	0.4	0.3	3.0	3.0	2.5	5.4	5.2	4.6	1.4	1.2
	Thickness of Sediment at t_{100} (inches)		4.0	4.2	4.8	5.5	5.4	5.7	4.2	5.2	5.2	4.0	4.4	4.5	4.5	4.6
	Time for Supernatant to Leach through Sample (days)			14.0	2.2	2.5	2.3	1.4	11.0							
	Thickness of Sediment after Finish of Leaching (inches)		3.3	3.5	4.1	4.4	4.5	5.0	3.5	4.0	4.0	3.5	3.4	3.5	3.8	3.9
	Vertical Shrinkage Due to Capillary Effects (%)		17.5	16.7	14.6	20.0	16.7	12.3	16.7	23.1	23.1	12.5	22.7	22.1	15.6	15.2
	Average Permeability (10^{-7} cm/sec)		28	37	1100	703	1020	1510	126	50	56	79	79	74	426	326
	Final Average Water Content (%)		121	128	148	152	154	158	128	110	103	127	110	121	133	144
	Final Average Dry Density (pcf)		32.8	38.3	33.2	32.4	31.6	30.5	34.3	35.8	40.6	33.5	33.8	33.4	36.8	38.9
	Average Shear Strength (psf)	Without Capillary Effects	63	43	44	40	55	54	41	45	47	40	37	37	37	31
		With Capillary Effects	139	96	88	79	87	91	121	143	152	120	150	148	79	76

of the pollution potential of the treated materials. The data were calculated on both a dry weight and a wet weight basis, but the results given in Table 6-3 are on a wet weight basis.

DISCUSSION

Very little work directly related to the leaching behavior of dredged materials has been reported in the literature. However, results of some indirectly related studies may aid in the interpretation of the results of this test program. Toth and Gold (1970) studied the effects of clay sediment additions to sandy soils on the loss of some plant nutrient elements, and they found that (a) when the clay sediment, beach sand, or Lakewood sand were treated with fertilizer and/or lime stone and leached with the equivalent of 4 inches of rainfall, the leaching losses of calcium, magnesium, and potassium ions were the lowest from the clay sediment, and (b) when clay sediment was added to the beach sand or Lakewood sand at 30 percent by weight, and the mixtures limed and fertilized and then leached with the equivalent of 4 inches of rainfall, the leaching losses of potassium and magnesium were markedly reduced when compared to pure beach sand or Lakewood sand. On the basis of these studies, they concluded that the addition of clay sediment to sandy soils will help in the retention of fertilizer cations and thereby reduce leaching losses. They further stated that the principal factors that regulate the loss of the cations (sodium, potassium, calcium, and magnesium) from the soil are (a) cation exchange capacity, (b) percentage of clay, (c) nature of the clay mineral in the clay fraction, and (d) the organic material content.

Table 6-3

Chemical Analyses of Leachates

	Sample Identification	Total Solids	Volatile Solids	Dissolved Solids	Suspended Solids	Volatile Suspended Solids	Silica (SiO_2)	Turbidity	Hydrogen Ion Concentration (pH)	Cadmium (Cd)	Calcium (Ca)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Mercury (Hg)	Potassium (K)	Sodium (Na)
		%	%	%	%	%	%	JTU		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Blank	C2DM	0.05	0.03	0.03	-	-	-	48	8.6	-	59	5.6	5	3.8	2.5	2.1	7
	C3TO	0.24	0.06	0.05	0.19	0.03	0.10	950	8.8	0.1	70	8.4	63	5.0	1.1	28.8	16
	C3TO	0.33	0.12	0.13	0.20	0.04	0.08	1000	8.7	-	118	5.3	63	4.8	7.6	28.0	21
	C5CO	0.08	0.04	0.07	0.01	0.01	0.02	37	9.1	0.1	33	4.5	4	3.6	2.4	5.2	36
	C22TO	0.16	0.11	0.13	0.03	0.02	0.01	115	8.7	-	76	3.5	8	4.7	4.2	13.1	21
	C22TO	0.20	0.07	0.08	0.12	0.02	0.10	800	8.8	0.1	67	2.2	36	4.5	1.0	20.8	18
	C22TO	0.27	0.05	0.11	0.16	0.02	0.06	900	8.7	-	138	5.1	47	1.9	3.5	28.4	41
	C27MM	0.73	0.06	0.59	0.14	-	0.09	920	8.7	-	120	8.0	34	4.2	12.1	42.3	128
C22TO	2% CaO	0.99	0.14	0.06	0.93	0.10	0.59	>1000	6.8	-	230	5.9	290	4.9	2.7	55.0	13
	4% CaO	1.08	0.22	0.16	0.92	0.17	0.50	>1000	10.2	-	472	6.5	252	2.7	3.0	63.0	161
	6% CaO	0.38	0.05	0.03	0.36	0.04	0.21	>1000	8.6	-	149	5.3	100	3.0	3.5	33.0	10
	2% NaCℓ	1.91	0.29	0.29	1.62	0.23	1.10	>1000	8.7	-	300	3.8	480	5.2	7.4	68.6	445
	3% NaCℓ	2.00	0.26	0.72	1.28	0.16	0.84	>1000	8.5	-	276	4.0	394	3.0	14.4	99.8	1490
	4% NaCℓ	1.91	0.29	0.91	1.00	0.15	0.66	>1000	8.5	-	130	3.8	352	2.5	8.2	93.5	1980
	2% $CaCO_3$	1.52	0.20	0.07	1.45	0.17	0.98	>1000	8.7	0.1	340	3.0	413	4.9	9.8	48.6	18
	4% $CaCO_3$	3.14	0.44	0.07	3.08	0.41	2.00	>1000	8.5	-	1205	6.3	778	7.8	12.6	75.4	25
	6% $CaCO_2$	0.94	0.16	0.09	0.85	0.11	0.53	>1000	8.8	-	260	2.7	252	1.7	2.4	41.4	15
C27MM	4% CaO	0.84	0.11	0.67	0.17	-	0.06	900	11.8	0.1	334	5.0	29	4.5	12.2	43.6	139
	1% CaCℓ	0.94	0.19	0.83	0.12	0.03	0.05	970	8.5	0.1	364	9.4	24	5.1	5.1	56.4	141
	2% $CaCℓ_2$	0.85	0.17	0.74	0.11	0.07	0.01	580	8.6	-	390	4.3	15	3.7	2.7	56.1	136
	4% $CaCℓ_2$	1.03	0.26	0.87	0.16	0.10	0.04	700	8.4	-	739	5.2	21	4.4	8.9	50.5	154
	1% Resor.	0.62	0.05	0.54	0.08	-	0.04	350	9.0	-	112	3.7	19	4.2	3.7	53.3	136
	2% Resor.	0.62	0.07	0.56	0.06	0.04	0.01	430	8.4	0.1	89	5.6	8	4.3	3.9	47.1	138
	3% Resor.	0.65	0.08	0.61	0.05	0.01	0.02	980	9.0	-	85	4.6	11	3.3	7.2	51.4	149

Thornton and Blanc (1973) examined the possibilities of treating leachates from a sanitary landfill by chemical coagulation and precipitation to aid in the removal of biochemical oxygen demand, iron, calcium, and magnesium. They concluded that, of the chemicals tested for the coagulation and precipitation of leachates, lime produced the best results. A substantial reduction of certain leachate contaminants, such as color, suspended solids, and multivalent cations, could be achieved by use of lime treatment. However, significant removal of other dissolved solids and soluble organics, which account for the major portion of the BOD, was not observed. The required lime dosages were on the order of 300 mg/ℓ to 600 mg/ℓ. Optimum lime dosage varied with leachate strength; the higher the acidity of a leachate, the greater the required lime dosage to accomplish a given degree of removal.

This test program is primarily concerned with geotechnical engineering aspects of dredged materials, that is, the stabilization of a dredged material landfill so that it might serve some useful purpose. Therefore, the criteria for judging the relative effectiveness of the various chemical additives were the shear strength, deformability, permeability, and density of the materials and the pollution potential of the leachates. The initial slurry concentrations used in the laboratory tests were kept as close as possible to observed field conditions so that the results would be more meaningful in predicting field behavior. Unfortunately, the initial condition for each individual test could not be well controlled, because the coarser particles settled rapidly from suspension at the planned concentrations, which were 180 mg/ℓ and 120 gm/ℓ for the C22TO and C27MM materials, respectively. However, observations indicate that the coarser portion may not have much effect on the overall behavior of the sediment, since it settled quickly to form the bottom portion of the sediment in each case. Therefore, the data in Tables 6-1 and 6-2 can be used for comparative purposes, and a comparison of the plots of sediment volume versus time for the sedimentation tests show that:

(a) The lime treated materials reached 100 percent sedimentation in a shorter time than untreated material, and larger, but relatively stable, sediment volumes were formed with the treated soils; this may be due to the flocculation and cementation effects of the lime.

(b) Calcium carbonate and sodium chloride gave essentially no improvement for the C22TO material, but they did improve the C27MM material; specifically, 100 percent sedimentation was reached in a shorter time and large, but relatively stable, sediment volumes were formed. However, calcium chloride and resorcinol were ineffective for both materials tested; this may be because the concentrations of the slurries in this series of tests were higher than those in the flocculation-sedimentation tests (which were 50 gm/ℓ). Therefore, the flocculants judged to be effective in Chapter 5 may not all be as effective for the concentrations used in this series of tests.

(c) All of the chemicals tested were more effective in forming stable sediments with the C27MM material than with the C22TO material; this may be due to coarser particle size distribution and lesser biological activity of the C27MM material.

Because of seepage force effects during the sedimentation-leaching tests, it would be expected that sediment densities would be greater and sedimentation times shorter than for the sedimentation tests. Although the data in Tables 6-1 and 6-2 show that the sedimentation times, t_{100}, and corresponding sediment volumes were slightly less for the sedimentation-leaching tests, a comparison of the data for treated and untreated samples in both tests show that the sedimentation (or consolidation) behavior greatly improved with lime treatment. This suggests that the physico-chemical forces are more effective than seepage forces in determining the consolidation behavior of the sediments. However, in improving the final densities of the sediments the effects of seepage forces are greater than those of physico-chemical forces.

As leaching continued, the sediment became unsaturated and the capillary forces caused shrinkage, but no particular trends could be observed. In general, the vertical shrinkage due to capillary effects varied from 15 to 20 percent. Complete leaching required months for most of the untreated materials and for those treated with ineffective chemicals. For these samples the supernatant liquid was syphoned out after two to three months of settling, at which times no more significant settlement could be observed. Therefore, the times for complete leaching of these samples are not given in Tables 6-1 and 6-2. Complete leaching was obtained in 3 to 11 days for lime treated materials; this is another indication of the effectiveness of lime treatment.

The average permeabilities of lime treated materials increased to 20 to 30 times those of the untreated samples for both materials tested. Calcium carbonate and sodium chloride treatment increased the permeability of the C27MM material by a factor of 10; this may again be due to flocculation effects, resulting in the formation of a more open structure. Other chemicals used resulted in an insignificant increase in permeability; this may be due to ineffective flocculation under the test conditions. There was little difference in the final water contents and final dry densities of the treated and untreated materials, except for those treated with lime. These materials had higher final water contents and lower final dry densities due to the more open and stable structure resulting from flocculation and cementation effects.

As would be expected, shear strengths increased as leaching reached completion and capillary tension become more effective. Lime treated materials had lower shear strengths due to lower dry densities when compared with untreated samples, both with and without capillary effects. The curing of lime treated samples (after completion of leaching) in a humid room at 80°F for two weeks led to no significant increases in shear strength. Thus, lime was not effective in increasing the shear strength of the samples with high water contents (140 to 150 percent) at this stage. All other samples had similar shear strengths for the test conditions which approximated in-situ conditions. For purposes of comparison, unconfined compressive strengths of compacted samples of the C22TO material were determined after 14 days of curing in a humid room. The strengths of lime treated samples were as much as twice those of untreated samples, and the strength increased almost linearly with the percentage of lime added. This suggests that the cementation effects of lime are very effective in increasing strength for the material at a water content of about 30 percent. A detailed study of compacted sample strengths after curing for materials treated with lime and cement is presented in Chapter 10. Calcium carbonate treatment resulted in no significant strength increase, but sodium chloride treatment resulted in a slight decrease when compared to untreated materials, perhaps due to the deflocculation effect at higher percentages of sodium chloride.

The frequent scatter in the results of the chemical analyses of the leachates is due largely to the heterogeneous nature of the dredged materials; this scatter makes it somewhat difficult to draw specific conclusions, but, based on observations during the leaching process and on information from the literature, it is possible to infer the following general trends:

1. Treatment with effective flocculating chemicals results in large initial sediment volumes and a more open structure which allow more of the fine solids to leach from the material. Table 6-3 shows the increase in total and suspended solids contents of the leachates from the materials treated with flocculants as compared with untreated materials; this is true even after the quantity of supernatant liquid syphoned off and the fines incorporated in the flocs are taken into account. For the different dredged materials tested, the finer materials produced more solids in the leachate for the same percentage of the flocculant used.

2. Although the volatile and suspended volatile solids contents in the leachates of the treated materials increased, the respective ratios of total to suspended solids contents were the same (10 to 20 percent) as those in the leachates from the untreated materials (when sufficient quantities were obtained for comparison).

3. Since sodium and calcium chlorides were completely dissolved, the leachates from materials treated with these chemicals showed correspondingly higher dissolved solids contents. For the partially dissolved chemicals, such as lime and calcium carbonate, the leachates did not show significant variations in dissolved solids contents when compared with those in the leachates of the untreated materials.

4. Although higher silica contents correspond directly to greater amounts of suspended solids, on a wet weight basis, as shown in Table 6-3, the data on a dry weight basis (not presented herein) indicate that the amounts of silica in the leachates were directly related to the different dredged materials tested, that is, the results depend on the composition of the material. Furthermore, the reactions of additives with the silica-rich C22TO material may also release more silica to the leachate. On the other hand, this increase was insignificant in the silica-poor C27MM material.

5. In most cases the solids content of the leachates caused turbidities in excess of those that could be measured by the turbidometer, hence, no correlations between the solids content and turbidity of the leachates could be obtained.

6. In general, the pH of the leachates ranged from about 8.5 to 9.0 for both treated and untreated samples; this similarity may have been due to bio-chemical reactions in the sediment.

7. The concentrations of all metallic elements were calculated on both a wet weight basis (weight of element divided by volume of leachate) and a dry weight basis (weight of element divided by weight of total solids), but the data presented in Table 6-3 are on a wet weight basis only; this basis is more meaningful for the leachate samples.

However, in the interpretation of test results both bases were used, and the following trends were noted:

(a) The leachates of the lime, calcium carbonate, calcium chloride, and sodium chloride treated samples exhibited increases in calcium and sodium ion concentrations, respectively, and these increases were directly related to their treatment additives. The increase of calcium ion concentrations of some leachates (from calcium ion treated C22TO material) were not directly proportional to the percentage of the additive used for treatment; this may be due to (i) volume of supernatant liquid syphoned off, (ii) the variation of the solids contents in the leachates, and (iii) the physico-chemical interaction in the sediments.

(b) The ion concentrations of calcium (for the sodium chloride treated material), iron, and potassium in the leachates from the C22TO material increased on a wet weight basis; however, there was no significant variation on a dry weight basis. This implies that the increase in those ion concentrations were mainly due to the increase in suspended solids content and the cation exchange effects were insignificant. Furthermore, since there were no significant changes in suspended solids in the leachates from the treated and untreated C27MM material, no significant variations were shown on either a wet or a dry weight basis; this implies that the calcium, iron, and potassium ions were associated with the leached solids.

(c) When comparing leachates from treated and untreated materials, no significant changes in cadmium, copper, lead, and mercury ion concentrations were observed in the data calculated on a wet weight basis. Each of the ion concentration variations were about the same for corresponding treated and untreated materials. On the other hand, no general trends for these ion concentrations could be found in the data calculated on a dry weight basis; this suggests that these ions were dissolved in the slurry and were inactive with the additives tested.

In brief, based on the chemical analyses of the leachates, it appears that there were no significant changes in the water quality of the leachates when the materials were treated with various additives. However, there were increases in the solids contents due to flocculation by additives, increases in the specific ion concentrations directly related to the additive, and increases in the dissolved solids contents corresponding to the dissolved additives. From the overall comparison of chemical additives used, lime seems to be the most effective. It stabilized the soil structure, increased the permeability of the sediment, and increased the strength of compacted samples after curing. The optimum percentages that are required vary with different dredged materials; in general, higher percentages were more effective, but two to four percent of lime by weight of solids should be sufficient to improve the stated engineering properties.

CONCLUSIONS

As far as strength and density are concerned, the effectiveness of chemical additives to stabilize dredged materials is far below that of compaction, evaporation, sand drains with preloading, etc. However, in the case of hydraulic fills of cohesive dredged materials in diked containment areas, the latter methods are diffcult to apply. In these situations lime may improve sedimentation and drainage conditions sufficiently to allow earlier utilization of the landfill site. Lime treatment may also change the sediment cahracteristics so other stabilization methods can be more effectively applied. Some of the conclusions that can be drawn from the test results are:

1. Of the chemical additives tested, lime showed the most promise for improving the engineering properties of dredged materials. It flocculates the dredging slurry, thereby causing a more rapid sedimentation and a more open and stable sediment structure. The permeability of the resulting sediment may be as much as 30 times that for the untreated material and drainage is much more rapid.

2. The lime treated materials resulted in sediments with lower shear strengths than those for untreated materials; this is due to the lower density of the more open structure of the sediment. However, the shear strengths after two weeks curing, of the lime treated compacted materials were as much as double those for untreated materials.

3. Based on the test results and engineering and economic considerations, two to four percent lime by weight of solids should be

adequate to achieve significant improvement in the behavior of dredged materials; the exact amount would depend on the characteristics of the dredged material.

4. Based on results reported in the literature, lime is effective in treating sanitary landfill leachates to reduce color, suspended solids, and multivalent cations.

5. Among the other chemical additives tested, calcium carbonate and sodium chloride were also effective for improving the sedimentation characteristics and permeability of the sediments of the C27MM material; however, these additives were only effective for the one material and were not as effective as lime.

6. Based on the chemical analyses of the leachates, there were no significant changes in the water quality of the leachates when the dredged materials were treated with additives; except for an increase in the solids due to flocculation increases in the specific ion concentration were directly related to the additives, and increases in the dissolved solids corresponded to the additives used.

CHAPTER 7

REPEATED LEACHING TESTS

The effect of groundwater pollution by leachates from dredged sediments is one important criterion for judging the acceptability of dredging disposal in diked containment areas. In general, two potential ecological problems are created by a sanitary landfill -- polluted leachates and gas generation from organic decomposition. In the case of landfills composed of dredged materials, gas generation does not cause a serious environmental problem. However, the leaching of polluted dredged materials may occur as the water drains from them and as surface water filters through them. The contaminants carried by a leachate are dependent on the composition of the dredged material and the simultaneously occurring physical, chemical, and biological activities within the fill. In an effort to assess the long-term pollution potential of leachates from landfills of dredged materials, a series of repeated leaching tests were conducted in the laboratory. Since a typical repeated-leaching test frequently lasted for months due to the low filtration rates of the dredged materials tested, bio-chemical reactions may have occurred during the tests; however, the laboratory test program concentrated only on the chemical analysis of the leachates. In addition, the effects of lime, which was the most promising chemical additive, on the improvement of the leachate quality and the engineering behavior of the sediments was studied.

SAMPLE PREPARATION AND TEST PROCEDURES

The methods of sample preparation and the procedures for conducting a repeated leaching test, as well as the methods for chemical analysis of the leachates, are given below:

(a) Calculate the volume of slurry required to produce a sediment of the desired thickness.

(b) Pour the thoroughly mixed slurry into the repeated leaching chamber (similar to the sedimentation-leaching chamber described in Chapter 6, with the difference that the repeated leaching chamber was a 24-inch (60-cm) high and 6-inch (15-cm) diameter cylinder).

(c) Allow the material to settle without drainage for two to three days until the supernatant fluid is nearly clear and the sediment thickness is stabilized, i.e., no further significant settlement of the sediment surface is observed.

(d) Syphon out the supernatant liquid and gradually fill with deionized water until the desired water level is reached.

(e) Open the outlet valve to allow drainage, and continue adding deionized water to maintain the desired water level; collect the leachate in one gallon (4 liter) batches at least four times or until clear. No specific methods were used to preserve these lechate samples.

(f) Record the surface levels of the water and the sediment, the weight of leachate obtained, and/or the amount of water added; these data are used in the permeability calculations.

CHEMICAL ANALYSES

The procedures followed in the chemical analyses of the leachates are described below.

Total Solids, Volatile Solids, and Silica

To determine total solids, a sample of leachate was added to a preweighed crucible, quickly weighed to avoid evaporation loss, and dried overnight at 105°C. After weighing, the volatile solids were obtained by igniting the sample at 600°C for one hour. The ignited sample was digested for one-half hour on a steam bath in a solution containing approximately 10:1 concentrated hydrochloric acid and concentrated nitric acid. It was then filtered into a preweighed Gooch crucible, and the filtrate was used for metal analyses. After the contents of the crucible were dried overnight at 105°C, the weight of the remaining solids was taken to be a measure of the silica content of the original sample.

Dissolved Solids, Suspended Solids, and Volatile Suspended Solids

Following the same procedures as those used for the determination of the total solids and volatile solids for a sample of filtered leachate, the dissolved solids and volatile dissolved solids were obtained. After all four of these percentages were calculated on a weight-of-solution basis, the suspended solids content was obtained from the difference between the total solids and the dissolved solids contents. Since the percentages of total solids for all of the leachates collected were less than 0.65 percent, no correction for the volume of water in the original leachate and in the filtered leachate were necessary.

Turbidity and pH

Both turbidity and pH were determined on a sample of the original leachate. Turbidity readings were taken on a portable Hach (DR-EL) kit and read in JTU units. The pH was measured with a Sargent-Welch pH meter (Model NX).

Metals

The filtrates from the total solids were used to determine the concentrations of cadmium, calcium, copper, iron, lead, mercury, potassium, and sodium by atomic absorption or flame emission on a Jarrell-Ash Atomic Absorption Spectrophotometer (Model 82-500). Standards were prepared according to those outlined in FWPCA Methods for Chemical

Analysis of Water and Wastes (November 1969), and results less than 0.1 ppm were not reported.

PRESENTATION OF TEST RESULTS

Twenty-two individual repeated leaching tests were conducted on seven different dredged materials from five harbors in the Great Lakes area. The test conditions for each sample and the quantities of the leachate samples collected are summarized in Table 7-1. The notations A, B, or C after each material denotes the difference in sample thickness and average head, while the notation "1% CaO" means that the material was treated with one percent (by weight of solids) lime. The average permeability of the sediment during each sample collection period was calculated by use of the relationship for a constant head permeability test, and the results are given in Table 7-2.

All of the leachates collected were chemically analyzed, and the results are summarized in Tables 7-3 through 7-9; each table contains the data for a separate dredged material. Although most test results are considered reliable to two significant figures, an attempt was made to establish columns of data according to a consistent decimal format, and this procedure sometimes caused the number of significant figures to vary within a column. Insofar as possible, units were selected to maintain consistency. All data are expressed as percentages of the weight of the solids to the total wet weight of the sample; the conversion to a dry weight basis is accomplished by simply dividing the wet weight basis percentage for a constituent by the ratio of the total solids to the total sample, taking proper account of the units of each.

Table 7-1

Test Conditions for Each Sample and Quantities of Leachate Collected

Sample Number		Sample Thickness (inches)	Average Head (inches)	Hydraulic Gradient	Quantities of Leachate Collected (gallons)									
					1	2	3	4	5	6	7	8	9	10
C22TO	A	4.5	14.5	3.2	1.0	1.0	1.0	1.0	1.0					
	B	1.8	4.5	2.5	0.25	0.12	0.12	0.75	1.0	1.0				
	C	1.9	4.5	2.4	0.5	0.25	0.25	1.0	1.0	1.0				
	1% CaO	6.5	14.0	2.2	1.0	1.0	4.0	4.0						
C27MM	A	4.2	13.0	2.1	1.0	1.0	1.0	1.0	1.0	1.0				
	B	1.3	4.0	3.1	0.2	0.25	0.1	1.0						
	C	1.4	4.0	2.9	0.5	0.12	0.12	0.12	0.12	0.16	1.0	1.0	1.0	1.0
	1% CaO	6.1	13.0	2.2	1.0	1.0	4.0	4.0	4.0					
C28CI	A	6.5	16.0	2.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0			
C80TO	A	3.3	15.5	4.7	0.5	1.0	1.0	1.0						
	B	3.2	15.5	4.9	0.5	1.0	1.0	1.0						
	C	3.3	15.5	4.7	0.5	1.0	1.0	1.0						
	1% CaO	6.8	14.5	2.2	1.0	1.0	4.0	4.0						
D1DM	A	4.5	14.0	3.1	0.7	1.0	1.0	1.0	1.0	1.0				
	B	4.5	5.5	1.2	0.12	0.3	0.08	1.0	1.0					
	1% CaO	6.9	13.5	2.0	1.0	1.0	4.0	4.0	4.0					
D3TO	A	4.4	16.5	3.8	0.5	1.0	1.0							
	B	4.4	5.5	1.3	0.15	0.2	0.3	1.0	1.0					
	1% CaO	6.3	14.5	2.3	1.0	1.0	4.0	4.0	4.0					
D4CO	A	5.8	15.0	2.6	0.6	1.0	1.0	1.0						
	B	3.8	5.2	1.4	0.25	0.25	1.0	1.0	1.0	1.0				
	1% CaO	6.4	13.5	2.3	1.0	1.0	4.0	4.0	4.0					

Table 7-2

Average Permeability of Sediments During Each Leaching Period

Sample Number		Average Permeability (10^{-7} cm/sec)									
		1	2	3	4	5	6	7	8	9	10
C22TO	A	27	28	22	28	18					
	B	25	15	14	37	32	27				
	C	35	12	20	27	25	18				
	1% CaO	187	180	79	66						
C27MM	A	41	49	32	42	38	42				
	B	60	28	34	39						
	C	71	35	15	73	49	23	50	78	32	61
	1% CaO	370	178	150	99	122					
C28CI	A	2700	2570	2400	2390	2110	2130	1290			
C80TO	A	8	12	7	6						
	B	7	11	8	6						
	C	8	10	8	6						
	1% CaO	104	86	79	82						
D1DM	A	45	56	41	37	33	38				
	B	34	32	28	22	27					
	1% CaO	211	286	237	266	248					
D3TO	A	7	8	4							
	B	36	27	31	31	28					
	1% CaO	165	110	104	92	98					
D4CO	A	14	9	16	7						
	B	47	40	42	45	48	24				
	1% CaO	653	390	270	202	130					

Table 7-3

Chemical Analyses of Leachate from C22TO

Sample Identification	Total Solids	Volatile Solids	Dissolved Solids	Suspended Solids	Volatile Suspended Solids	Silica (SiO_2)	Turbidity	Hydrogen Ion Concentration (pH)	Cadmium (Cd)	Calcium (Ca)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Mercury (Hg)	Potassium (K)	Sodium (Na)
	%	%	%	%	%	%	JTU		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
A1	0.13	0.02	0.12	0.01	-	0.03	155	8.7	2.8	44	0.9	39	4.3	2.8	31.8	209
A2	0.03	-	0.03	-	-	0.01	55	8.6	1.2	43	1.4	30	2.3	1.1	6.3	28
A3	0.08	0.02	0.08	-	-	0.03	40	8.3	0.1	140	0.5	8	0.5	2.5	9.2	57
A4	0.04	0.01	0.04	-	-	0.01	31	7.6	0.1	77	0.9	12	0.5	-	3.7	13
A5	0.03	0.01	0.03	-	-	0.01	19	7.8	-	51	0.2	9	0.4	-	2.9	12
B1	0.08	0.03	0.04	0.04	-	0.03	275	8.1	1.0	89	2.0	99	4.6	4.3	12.2	8
B2	0.03	0.01	0.01	0.02	-	0.02	11	8.5	1.6	59	2.0	43	5.1	3.4	4.6	7
B3	0.04	0.02	0.03	0.01	-	0.03	28	8.2	1.2	57	2.4	30	5.1	2.0	2.4	5
B4	0.02	-	0.02	-	-	0.01	45	8.3	-	18	0.2	9	-	-	11.8	4
B5	0.01	-	0.01	-	-	-	35	8.2	-	22	0.2	4	-	-	5.1	4
B6	0.01	-	0.01	-	-	-	32	8.2	-	31	0.4	5	-	-	2.6	3
C1	0.09	0.02	0.04	0.05	-	0.03	800	7.9	1.9	40	2.5	99	3.7	1.9	18.6	8
C2	0.10	0.02	0.10	-	-	0.04	96	8.7	4.1	55	3.0	155	4.2	4.8	17.3	159
C3	0.03	0.02	0.03	-	-	0.01	80	8.4	-	43	0.4	5	-	-	2.6	3
C4	0.01	-	0.01	-	-	0.01	22	8.3	-	26	0.2	4	-	-	5.3	3
C5	0.01	-	0.01	-	-	-	12	8.1	-	17	0.2	3	-	-	4.4	3
C6	0.01	-	0.01	-	-	-	23	8.1	-	18	0.2	3	-	-	4.5	3
1% CaO 1	0.14	0.09	0.13	0.01	0.01	0.01	20	12.0	-	422	2.1	1	-	-	2.2	5
1% CaO 2	0.12	0.07	0.11	0.01	-	0.01	27	11.6	-	388	2.9	5	-	-	2.9	4
1% CaO 3	0.07	0.04	0.06	0.01	-	0.01	17	9.8	-	170	1.8	2	-	-	3.6	6
1% CaO 4	0.03	0.02	0.02	0.01	-	0.01	26	8.4	-	61	2.1	1	-	-	2.7	5

Table 7-4

Chemical Analyses of Leachate from C27MM

Sample Identification	Total Solids	Volatile Solids	Dissolved Solids	Suspended Solids	Volatile Suspended Solids	Silica (SiO_2)	Turbidity	Hydrogen Ion Concentration (pH)	Cadmium (Cd)	Calcium (Ca)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Mercury (Hg)	Potassium (K)	Sodium (Na)
	%	%	%	%	%	%	JTU		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
A1	0.34	0.03	0.31	0.03	-	0.02	240	8.0	1.6	139	3.1	170	4.8	3.2	65.3	458
A2	0.08	0.03	0.08	-	-	-	32	8.7	-	165	0.2	6	0.3	-	11.9	44
A3	0.03	0.02	0.03	-	-	-	38	8.5	-	56	0.2	2	-	-	2.6	8
A4	0.02	0.01	0.02	-	-	-	23	8.3	-	34	1.2	4	-	-	2.4	4
A5	0.02	0.01	0.02	-	-	-	14	8.3	-	37	0.3	1	-	-	1.9	3
A6	0.02	0.01	0.02	-	-	-	9	8.2	-	40	0.5	4	-	-	2.3	3
B1	0.57	0.02	0.56	0.01	-	0.04	280	8.6	2.3	129	1.7	73	3.8	5.9	27.2	1445
B2	0.64	0.02	0.64	-	-	0.02	264	8.6	1.9	128	1.3	73	3.8	5.8	26.9	1630
B3	0.09	-	0.09	-	-	0.02	72	8.7	1.5	60	2.3	36	2.7	4.1	19.5	165
B4	0.16	0.04	0.06	0.10	0.02	0.04	>1000	8.0	-	24	1.2	44	-	-	30.0	48
C1	0.62	0.02	0.59	0.02	-	0.04	750	8.3	1.6	139	3.7	141	5.9	9.3	75.2	244
C2	0.29	-	0.26	0.03	-	0.02	430	8.7	2.0	61	4.0	165	17.7	12.7	49.5	559
C3	0.14	-	0.12	0.02	-	0.03	61	8.6	1.9	39	1.4	74	3.1	2.5	18.6	175
C4	0.12	-	0.12	-	-	0.03	54	8.7	2.8	23	0.9	117	2.2	4.5	15.1	171
C5	0.07	-	0.07	-	-	0.04	36	8.5	0.2	22	1.5	77	4.9	5.8	13.7	161
C6	0.13	0.01	0.07	0.06	-	0.04	45	8.3	0.1	104	1.3	20	3.4	2.9	15.2	149
C7	0.02	0.01	0.01	-	-	-	39	8.1	-	24	0.2	4	-	-	5.6	14
C8	0.01	0.01	0.01	-	-	-	27	8.0	-	8	0.3	6	-	-	9.1	6
C9	0.01	0.01	0.01	-	-	-	24	7.9	-	16	0.2	4	-	-	7.9	6
C10	0.01	-	0.01	-	-	-	6	8.0	-	17	0.2	1	-	-	4.5	5
1% CaO 1	0.22	0.12	0.17	0.05	0.04	0.01	35	12.2	-	708	2.7	1	-	-	24.4	6
1% CaO 2	0.19	0.08	0.14	0.05	0.02	0.01	29	12.1	-	717	4.5	4	-	-	6.0	12
1% CaO 3	0.13	0.05	0.09	0.04	-	0.02	23	11.7	-	454	1.1	1	-	-	3.3	4
1% CaO 4	0.05	0.03	0.05	-	-	0.01	27	8.4	-	90	0.6	2	-	-	3.8	6
1% CaO 5	0.03	0.01	0.03	-	-	0.01	24	8.4	-	49	0.9	1	-	-	4.2	6

Table 7-5

Chemical Analyses of Leachate from C28CI

Sample Identification	Total Solids	Volatile Solids	Dissolved Solids	Suspended Solids	Volatile Suspended Solids	Silica (SiO_2)	Turbidity	Hydrogen Ion Concentration (pH)	Cadmium (Cd)	Calcium (Ca)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Mercury (Hg)	Potassium (K)	Sodium (Na)
	%	%	%	%	%	%	JTU		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
A1	0.12	0.02	0.12	-	-	0.01	118	6.6	1.2	65	3.6	51	2.1	3.9	29.7	207
A2	0.27	0.01	0.27	-	-	0.02	20	7.5	1.1	321	0.8	27	4.3	7.4	38.6	196
A3	0.01	0.01	0.01	-	-	-	6	8.2	-	27	0.2	2	-	-	3.5	11
A4	0.01	-	0.01	-	-	-	4	8.2	-	13	0.2	4	-	-	4.6	8
A5	0.01	-	0.01	-	-	-	10	9.4	-	9	0.2	2	-	-	2.7	6
A6	0.01	-	0.01	-	-	-	4	9.4	-	12	0.2	1	-	-	2.0	3
A7	0.01	-	0.01	-	-	-	5	8.3	-	8	0.2	1	-	-	3.4	3

Table 7-6

Chemical Analyses of Leachate from C80TO

Sample Identification	Total Solids	Volatile Solids	Dissolved Solids	Suspended Solids	Volatile Suspended Solids	Silica (SiO_2)	Turbidity	Hydrogen Ion Concentration (pH)	Cadmium (Cd)	Calcium (Ca)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Mercury (Hg)	Potassium (K)	Sodium (Na)
	%	%	%	%	%	%	JTU		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
A1	0.28	0.03	0.27	0.01	-	0.03	120	8.0	5.6	88	3.4	188	3.6	4.7	35.4	326
A2	0.14	0.03	0.14	-	-	-	24	8.6	-	168	0.1	2	-	-	16.0	110
A3	0.03	0.01	0.30	-	-	-	22	8.5	-	35	0.2	4	-	-	3.7	22
A4	0.02	0.01	0.20	-	-	-	9	8.3	-	25	0.2	4	-	-	2.7	7
B1	0.32	0.03	0.31	0.01	-	0.03	146	8.0	8.1	106	1.9	72	4.7	4.3	48.0	409
B2	0.15	0.02	0.15	-	-	-	11	8.4	-	217	1.1	4	-	-	19.9	123
B3	0.03	0.02	0.03	-	-	-	20	8.6	-	42	0.1	4	-	-	4.6	27
B4	0.02	0.01	0.02	-	-	-	13	8.4	-	24	0.2	4	-	-	3.2	9
C1	0.17	0.01	0.17	-	-	0.04	92	8.0	5.0	65	4.2	63	4.5	5.3	34.1	180
C2	0.12	0.02	0.12	-	-	0.01	14	8.2	-	137	0.4	4	-	-	17.6	97
C3	0.02	0.01	0.02	-	-	-	18	8.4	-	28	0.1	4	-	-	3.6	15
C4	0.01	0.01	0.01	-	-	-	10	8.4	-	18	0.6	1	-	-	3.2	9
1% CaO 1	0.18	0.09	0.16	0.02	0.01	0.01	23	12.1	-	329	5.5	1	-	-	3.2	3
1% CaO 2	0.15	0.07	0.11	0.04	0.01	0.02	25	12.2	-	494	0.9	2	-	-	2.3	3
1% CaO 3	0.09	0.04	0.08	0.01	-	0.01	22	11.7	-	320	0.9	1	-	-	3.3	4
1% CaO 4	0.05	0.02	0.04	0.01	-	-	23	8.4	-	112	0.4	1	-	-	2.9	4

Table 7-7

Chemical Analyses of Leachate from D1DM

Sample Identification	Total Solids	Volatile Solids	Dissolved Solids	Suspended Solids	Volatile Suspended Solids	Silica (SiO_2)	Turbidity	Hydrogen Ion Concentration (pH)	Cadmium (Cd)	Calcium (Ca)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Mercury (Hg)	Potassium (K)	Sodium (Na)
	%	%	%	%	%	%	JTU		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
A1	0.21	0.01	0.21	-	--	0.04	143	7.5	4.9	49	1.6	35	4.5	7.7	40.6	305
A2	0.12	0.02	0.12	-	-	-	59	7.7	-	210	0.2	32	-	-	7.1	59
A3	0.02	0.01	0.02	-	-	-	11	8.5	-	39	1.3	4	-	-	3.0	10
A4	0.01	0.01	0.01	-	-	-	11	8.5	-	17	0.3	5	-	-	3.1	7
A5	0.01	0.01	0.01	-	-	-	21	8.4	-	16	0.2	4	-	-	2.8	6
A6	0.01	0.01	0.01	-	-	-	15	8.3	-	14	0.2	7	-	-	3.5	4
B1	0.11	0.04	0.07	0.04	0.01	-	53	8.1	2.3	133	3.1	34	3.7	4.2	24.1	42
B2	0.11	0.04	0.08	0.03	-	0.03	83	8.1	3.7	114	2.6	61	4.3	6.9	27.0	35
B3	0.07	0.03	0.06	0.01	-	0.02	47	8.1	3.7	56	3.3	25	4.0	4.0	9.7	30
B4	0.06	0.02	0.05	0.01	-	-	46	8.3	-	92	0.7	8	-	-	14.0	24
B5	0.03	0.01	0.03	-	-	-	14	8.3	-	56	0.6	4	-	-	4.2	5
1% CaO 1	0.16	0.07	0.15	0.04	0.01	0.02	21	12.2	-	470	1.2	1	-	-	6.9	15
1% CaO 2	0.12	0.05	0.12	-	-	0.01	16	12.1	-	366	0.9	4	-	-	3.3	10
1% CaO 3	0.04	0.02	0.04	-	-	0.01	14	8.5	-	103	1.2	1	-	-	7.2	17
1% CaO 4	0.02	0.01	0.02	-	-	0.01	18	8.4	-	18	0.2	1	-	-	2.3	7
1% CaO 5	0.01	0.01	0.01	-	-	-	23	8.3	-	16	0.5	-	-	-	2.8	5

Table 7-8

Chemical Analyses of Leachate from D3TO

Sample Identification	Total Solids	Volatile Solids	Dissolved Solids	Suspended Solids	Volatile Suspended Solids	Silica (SiO_2)	Turbidity	Hydrogen Ion Concentration (pH)	Cadmium (Cd)	Calcium (Ca)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Mercury (Hg)	Potassium (K)	Sodium (Na)
	%	%	%	%	%	%	JTU		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
A1	0.06	0.01	0.06	-	-	0.01	48	8.4	1.7	102	2.1	48	5.5	6.0	10.9	16
A2	0.03	0.02	0.03	-	-	-	21	8.4	-	20	0.2	6	-	-	3.8	6
A3	0.03	0.02	0.03	-	-	-	15	8.2	-	42	0.2	5	-	-	2.9	5
B1	0.13	0.02	0.07	0.06	-	0.02	800	8.8	3.4	132	4.4	46	4.0	3.3	24.8	10
B2	0.10	0.06	0.07	0.03	-	0.02	82	8.8	2.1	85	3.4	19	2.8	3.1	22.2	45
B3	0.07	0.02	0.06	0.01	-	0.02	76	6.6	2.9	118	2.0	21	3.6	3.0	5.7	9
B4	0.02	0.01	0.02	-	-	0.01	33	8.4	-	47	0.2	4	-	-	4.8	7
B5	0.01	-	0.01	-	-	0.01	28	8.2	-	28	0.3	1	-	-	5.3	4
1% CaO 1	0.17	0.08	0.15	0.02	0.02	0.01	21	12.2	-	541	1.2	2	-	-	2.7	5
1% CaO 2	0.14	0.06	0.12	0.02	-	0.01	16	12.1	-	432	1.5	2	-	-	3.1	5
1% CaO 3	0.09	0.04	0.08	0.01	-	0.01	7	11.6	-	282	4.5	2	-	-	3.6	4
1% CaO 4	0.05	0.02	0.04	0.01	-	0.01	8	11.3	-	125	1.0	1	-	-	2.9	3
1% CaO 5	0.03	0.02	0.02	0.01	-	0.01	13	11.1	-	82	1.0	1	-	-	3.7	4

Table 7-9

Chemical Analyses of Leachate from D4CO

Sample Identification	Total Solids	Volatile Solids	Dissolved Solids	Suspended Solids	Volatile Suspended Solids	Silica (SiO_2)	Turbidity	Hydrogen Ion Concentration (pH)	Cadmium (Cd)	Calcium (Ca)	Copper (Cu)	Iron (Fe)	Lead (Pb)	Mercury (Hg)	Potassium (K)	Sodium (Na)
	%	%	%	%	%	%	JTU		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
A1	0.16	0.02	0.16	-	-	0.03	44	7.8	2.8	96	1.7	60	2.3	10.5	29.2	177
A2	0.06	0.04	0.06	-	-	-	13	8.3	-	17	1.4	8	-	-	7.1	17
A3	0.02	0.02	0.02	-	-	-	9	8.1	-	31	0.3	4	-	-	4.3	4
A4	0.03	0.02	0.03	-	-	-	10	8.3	-	33	0.2	2	-	-	2.6	3
B1	0.09	0.02	0.07	0.02	-	0.03	75	8.8	1.7	52	2.8	9	3.1	3.4	37.2	75
B2	0.11	0.06	0.10	0.01	-	0.03	90	8.7	-	78	1.5	54	3.9	4.6	21.1	42
B3	0.04	0.01	0.04	-	-	-	15	8.7	-	36	1.0	1	-	-	7.0	12
B4	0.04	0.02	0.04	-	-	-	10	8.5	-	66	0.5	1	-	-	5.1	6
B5	0.02	0.01	0.02	-	-	0.01	7	8.5	-	47	0.4	1	-	-	4.3	5
B6	0.02	0.01	0.02	-	-	0.01	14	8.5	-	48	0.2	2	-	-	4.5	4
1% CaO 1	0.13	0.07	0.12	0.01	0.01	0.01	22	12.0	-	272	1.1	2	-	-	6.0	17
1% CaO 2	0.08	0.04	0.07	0.01	0.01	0.01	20	11.8	-	191	1.1	1	-	-	6.1	14
1% CaO 3	0.05	0.02	0.05	-	-	0.01	5	11.5	-	105	0.8	1	-	-	6.0	7
1% CaO 4	0.03	0.01	0.03	-	-	0.01	6	10.8	-	17	0.8	1	-	-	3.1	2
1% CaO 5	0.01	0.01	0.01	-	-	-	4	8.5	-	32	0.1	1	-	-	5.1	5

DISCUSSION

In a brief description of the origin and general composition of leachates from landfills, MacNamara (1971) reported that:

> As initially emplaced and compacted, a landfill is moist, but usually aerobic. Biological uptake of the available oxygen plus additions of water, either by infiltration of precipitation in excess of runoff and evaporation or by actual contact with groundwater, facilitates development of anaerobic conditions. Hence, the actual conditions of breakdown in established landfills are anaerobic. The initial waters squeezed from the putrescible components and soil are usually acidic, dark greenish-black, possess high BOD and COD, and have a markedly offensive odor. As the rate of decomposition of soluble compounds comes into equilibrium with the movements of water through the landfill, ionic concentrations within the leachate tend to shift towards fixed ranges, each landfill seemingly having its own characteristics. With continued leaching ionic concentrations decline in general accordance with the laws of ion mobilities and biologic principles. Decomposition processes have important effects on the solubility of inorganic materials. For example, under anaerobic conditions sulfate is reduced to sulfide, which in turn, reduces ferric iron to soluble ferrous iron.
>
> In decomposition reactions by anaerobiosis, gaseous end products, methane, and carbon dioxide, are envolved. Nearly all of the methane will be evolved as a gas due to the low solubility of methane in water. Much of the carbon dioxide will be given off in the gaseous state, but some will remain in solution as carbonic acid and tend to lower the pH.
>
> As pH levels decrease, some leachates become laden with trace metals. Zinc and cadmium, the latter a common impurity in zinc used for zinc-galvanized iron, were recognized by the author in leachate emanating from a landfill in direct contact with groundwater. Chromium, manganese, copper, and lead were found in trace quantities in the same leachate, and in higher relative concentrations in the sediment in downstream reaches of nearby watercourses.
>
> As not all of the materials emplaced in a landfill are readily decomposible, the so-called putrescibles, evolution of environmentally degrading materials may continue for many years. Figure 7-1 depicts the generalized release curve derived from many works from landfills during their two or three years of life. Such a generalization cannot be drawn for heavy metals or other trace components, many of which become mobilized only after a protective coating has been destroyed. Landfills of some 20 to 30 years age have been found by the author to be still releasing iron, manganese, chromium, cadmium and zinc.

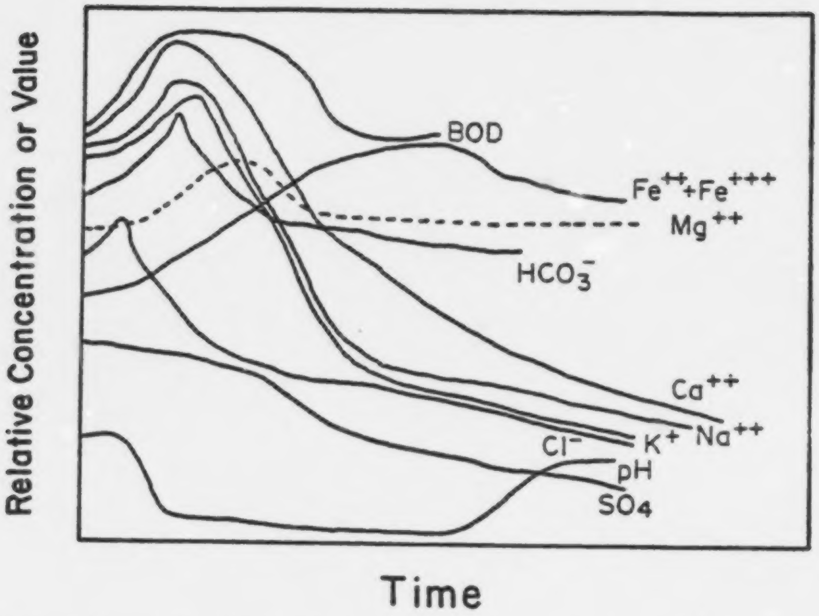


Figure 7-1. Idealized Shift in Partial Chemical Composition of Leachate over Time (After MacNamara, 1971)

The above description of leachates pertains primarily to leachates from landfills of municipally collected refuse, which is composed mainly of paper, metal, glass, food waste, etc. However, since the major components of the landfills considered in this investigation are relatively impermeable clayey silts that have lain on river or lake bottoms for rather long periods of time in some cases, the leachate problem may not be as serious as described by MacNamara (1971). In a general profile of some environmental considerations of sanitary landfill sites, Fischer and Woodford (1972) reported that:

> Normally, bacteriological contaminants are filtered from the leachate after only a few feet of travel through most soils, whereas suspended solids can travel over greater distances, creating significant groundwater pollution potential.

Moreover, a report entitled "Sanitary Landfills: The Latest Thinking" in the March 1973 issue of Civil Engineering stated that:

> Neither in the United States nor in Western Europe is leachate a problem, provided good design and operations practices are followed and necessary controls are exercised..... Cases are known where temporary increases in the organic content of nearby well waters have been experienced, but no contamination by organic matter or by microorganisms has resulted, and there were no public health concerns. The drastic change in leachate composition from that leaving the refuse to that observed in nearby wells is a result of dilution and, perhaps more importantly, the natural ability of soil to remove effectively many contaminants present in leachate.

In addition, several available methods to minimize the development of leachate problems were addressed in this latter report:

> First is proper site selection, in which the coarsest soils, fractured rock, and nearby surface waters are avoided. In these cases little if any removal of contaminants by the soil will be experienced. Second, by proper selection of cover material, its slope, plantings, and possibly by adding water in the form of recycled leachate, sewage sludge, or other water sources, one can postpone or hasten the rate of leachate production. Lastly, by contouring the bottom of the site and installing leachate collection devices, any leachate collected can be treated biologically or chemically, or otherwise disposed of safely.

Some work related to the use of lime treatment to improve landfills or leachates has also been reported. Arman and Munfakh (1970) stated that, when lime is added to organic soil, some of the calcium ions are used to satisfy the exchange capacity of the organics. This effect would alter the soil-water relationship and appears to reduce the formation of gas bubbles. Therefore, an increase in the coefficient of permeability for the soil mass can be induced. Andersland and Laza (1972) reported that mixing papermill sludge with a lime admixture can increase the permeability and contribute to easier drainage of papermill sludge landfills; however, the quantity of lime added was 10 percent by weight of solids. Thornton and Blanc (1973) indicated that a substantial reduction of certain leachate contaminants, such as color, suspended solids, and multivalent cations, can be achieved by using lime as a treatment additive. The required dosages, which caused coagulation and precipitation of solid particles in the leachates, was on the order of 300 mg/ℓ to 600 mg/ℓ. Although the literature suggests that several rather complicated bio-chemical reactions may occur in the landfill, the main purpose of this study is to investigate the long-term physical characteristics of the sediment, the pollution potential of the leachate, and the effectiveness of the lime additive for the improvement of both sediment and leachate properties.

Long-term Physical Characteristics of the Sediment

From Table 7-2 the average permeability of each untreated sample generally tended to decrease as the leaching continued; this may be due to (a) the compression of the sediment and the associated reduction in the pore sizes caused by seepage forces and (b) the clogging of drainage paths by eroded fines. In general, for the same material in an untreated condition, thicker sample depths and higher hydraulic gradients induced a lower average permeability of the sample; this may be due to higher seepage forces and a lesser degree of disturbance of the sediment. The exception manifested by the D1DM material may be attributed to the different in initial soil structure of A and B samples. Although the data in Table 7-2 shows that the finest C80TO material has the lowest average permeability and the coarsest C28CI material has the highest average permeability, the permeabilities of the intermediate materials do not vary monotonously with their clay contents. This suggests that, for the same testing conditions, the permeability of a sediment is dependent on both the grain size distribution (clay content and gradation) and the initial structure of the sediment.

Since all materials tested in this investigation were collected from fresh water regions, the dissolved solids contents were fairly low and the suspended solids were hardly detectable. Therefore, it is reasonable to use the total solids content, rather than the suspended solids content, of the leachates as a measure of the retentive ability of solids by the sediments. As illustrated in the second column of Tables 7-3 through 7-9, the total solids contents of most of the untreated samples decreased as leaching continued; this suggests that, as soon as the sediment structure is formed, the drainage paths are virtually fixed and the deionized water served more or less as a dilution agent. In the fourth leachage sample from material C27MM-B and the sixth leachage sample from material C27MM-C, the increases in total solids contents were due to disturbance of the sediment samples. In other cases all irregularities occurred in the first and second leachate samples; which were usually small and not truly representative of the volumes of leachates collected. There were no apparent general trends for the initial percentages of total solids contents (first gallon) of the leachates; this may be due to the combined effects of grain size distribution, sample thickness, hydraulic gradient, initial sediment structure, and permeability. All of the dredged materials tested were clayey silts, except for the sandy C28CI material. The initial total solids contents in the leachates of all samples (including the C28CI material) ranged from 0.1 to 0.3 percent, except for C27MM-B and C27MM-C, for which the initial total solids contents were about 0.6 percent; this was due mainly to the thinner sample depth (1.3 inches or 3 cm), the higher degree of disturbance, and the lesser retentive ability of the sediment.

As far as the declination rate of total solids contents (the decreasing rate of total solids percentage with the volume of water passing through the sample) was concerned, the thicker sample depths and the higher hydraulic gradients normally resulted in lesser declination rates of total solids contents. Exceptions were observed for the D1DM-A and D1DM-B materials which had a different initial structure, and the C28CI material, which had a different grain size composition and distribution. This leads to the conclusion that, for similar dredged materials and initial structures, a lower permeability induces a lesser declination rate of total solids contents; however, no general trend could be found with respect to initial total solids contents.

Long-term Pollution Potential of the Leachates

No standards concerned with pollution potential of leachates from landfills have been found in the literature survey. Therefore, in this discussion each item was self-evaluated and compared with field water samples from Penn 7 in Toledo, Ohio. The variations due to lime treatment were also studied. In general, Tables 7-3 through 7-9 show that the quantities of measured constituents of the leachates from untreated materials decreased as leaching progressed; this may be due to the formation of drainage paths and the dilution effects of deionized water. The slightly basic pH values did not change significantly during leaching and this could be attributed to the effect of the slightly basic deionized filling water. This may be another indication that no meaningful biochemical reactions took place during leaching.

The volatile solids, dissolved solids, suspended solids, volatile suspended solids, and silica contents of the leachates from untreated samples were very low and varied with those of the total solids contents, but no trends could be identified. Suspended solids and volatile suspended solids existed only in trace quantities and were difficult to detect. The turbidities of the leachates from the untreated samples were found to generally follow the same trends as the total solids contents. Precise correlations between turbidity and percentage of total solids content could not be found; this was probably due to the various types of particles and size distributions in the leachates.

Although some scatter was observed in the results for the metal contents in the leachates, all generally decreased as leaching proceeded. The initial value for each ion and its declination rate was found to depend on the composition of the dredged material and the test conditions. In general, sodium, calcium, iron, and potassium were present in higher amounts in the leachate; the initial concentrations of these ions ranged from tens to hundreds of parts per million. Lead, mercury, copper, and cadmium were present in lower amounts, and the initial concentrations of these ions ranged from about one to five parts per million.

After a detailed evaluation of the declination rate for each ion and a comparison of the data on a dry weight basis (not presented herein), the concentrations of potassium, lead, mercury, copper, and cadmium ions were found to decrease at about the same rate as that experienced for total solids contents (the ion concentration in the leachate reduced to about one-tenth its initial value after leaching with a volume of deionized water equal to five times the volume of the sediment. However, the concentrations of sodium and iron ions decreased at a higher rate than that of the total solids, whereas the concentrations of calcium ions decreased at a lower rate. This suggests that the sodium and iron ions replace the calcium ions in the exchangeable positions as leaching proceeds. These test results are not consistent with those shown in Figure 7-1 (MacNamara, 1971) which are based on a different type of landfill material.

In comparing the leachates of three materials from Toledo (C22TO, C80TO, and D3TO) with the field water samples from wells in the Penn 7 diked containment area at Toledo, the mean values of the field samples were of the same order of magnitude as all of the first-time leachates from each sample in the laboratory. One exception was the laboratory data for cadmium, which showed higher concentrations in the laboratory samples. Although of the same order of magnitude, most of the measurements on the field water samples yielded slightly higher values than those measured on the laboratory leachates. Since most of the field samples were taken prior to the deposition of any dredgings in the containment area, this situation reflects the relatively poor quality of the ambient groundwater. In the case of a few samples that were taken about three months after disposal of dredgings had commenced, there was simply not enough time for the leachates to enter the groundwater. A comparison of the water quality of the laboratory leachates with that of the groundwater at Penn 7 indicates that the leachates from the landfill will not lower the quality of the ambient groundwater; this condition may prevail at various other sites, and it must be given serious consideration when evaluating the pollution potential of leachates in the field.

Effects of Lime on Sediment and Leachate Properties

As shown in Table 7-2, the average permeability of the sediments increased by about one order of magnitude when the materials were treated with 1 percent lime (by weight of solids); this was due to the formation of a more open and stable structure. Although the sample thickness and hydraulic gradient were not the same for treated and untreated materials, these factors alone would not cause the permeability of the sediments to vary as much as observed. Furthermore, calcium ions from the lime may satisfy the exchange capacity of the organics and therefore reduce the formation of gas bubbles, thus controlling the long-term settlement of the sediments. A comparison of the data presented in Tables 7-3 through 7-9 for treated and untreated materials indicates that the addition of lime had the following effects:

1. The total solids contents increased slightly due to the formation of a more open and stable structure of the sediment.
2. The volatile solids contents increased greatly due to the fact that calcium ions from the lime apparently satisfied the exchange capacity of the organics and the separated organics were transferred with the deionized water to the leachate. Hence, the suspended solids and volatile suspended solids contents also increased slightly, but the dissolved solids did not change appreciably.
3. The silica content and turbidity decreased.
4. The pH increased to about 12 at the beginning of the test, probably because the lime treatment introduced large amounts of calcium ions into the leachate.
5. The sodium, ion, potassium, lead, mercury, and cadmium ion concentrations decreased due in all probability to the removal of organics which induced the absorption of these ions to the sediment particles; however, the copper ion concentrations were not changed very much.

In brief, when the materials were treated with lime, a more open and stable structure was formed, the permeability increased, more organics were removed through the leaching process, and the long-term settlement was reduced. Although the calcium ion concentration, volatile solids content, and pH value of the leachates from these treated sediments increased, the silica content, turbidity, and most of the other ion concentrations decreased. Based on experience, a higher percentage (perhaps 2 percent by weight of solids) of lime would be recommended to achieve increased and longer lasting improvements.

Comparison of Field and Laboratory Conditions

All of the laboratory tests were performed on relatively homogeneous materials under well drained conditions (namely, through a one-inch thick porous stone). However, the conditions that prevail in a typical field situation are generally not as idealized. For example, in the Penn 7 diked containment area in Toledo, the hydraulic gradient was considerably less than that in the laboratory and the bottom drainage was not as good. The gases created by digesting organics could not completely escape from the lower portion of the field sediments, thereby resulting in many visible cavities within the fill. There were horizontal stratifications due to putrid vegetation that grew during the warm dormant periods between dredging seasons, and vertical shrinkage cracks formed in the upper part of the landfill (top crust) due to evaporation. In addition, various other factors served to increase the heterogeneity of the landfill and enhance its filtration capacity.

CONCLUSIONS

Based on the data accumulated from an extensive series of repeated leaching tests, the following conclusion can be advanced:

1. Water samples from wells in the Penn 7 disposal area yielded chemical parameters that are of the same order of magnitude as those of the first-time leachates obtained from laboratory tests on three similar materials from Toledo; this suggests that the long-term pollution potential of leachates from landfills may not pose a serious problem in some cases, because the quality of the leachates improves rapidly with subsequent through-puts of leachate.

2. As a consequence of clogging, the average permeability of a dredged material tends to decrease with time as leaching continues; the range for the initial coefficient of permeability (15×10^{-7} to 60×10^{-7} cm/sec) for similar dredged materials may decrease by one-half after leaching with a volume of water equal to five times the sediment volume.

3. For similar materials and initial structures, thicker sample depths and higher hydraulic gradients resulted in lower average permeabiliites, and the declination rate of the total solids content decreased for the lower permeabilities; therefore, an increase in the hydraulic gradient causes an increase in the final percentage of total solids content.

4. Relative to the finer, more cohesive materials, the leachates from the well-graded, coarser dredged material (C28CI) had a higher total solids content at the beginning of leaching, a higher declination rate of total solids content, and a lower total solids content at the end of leaching; this may be due to the presence of larger pore sizes and less fines.

5. In general, all quantities measured in the leachates decreased with an increase in the volume of leachate drained; this was probably due to the development of steady drainage paths and the dilution effects of the deionized water. The concentration of each constituent was reduced to about one-tenth of its initial value after leaching with a volume of water equal to five times the sediment volume.

6. The slightly basic pH values did not change significantly during leaching; this could be due to the effect of the slightly basic deionized filling water, and it may be another indication that no drastic bio-chemical reactions took place during leaching.

7. Sodium and iron ions had a higher declination rate than that of total solids, but calcium ions had a lower declination rate; this suggests that the calcium ions are replaced by sodium and iron ions from the exchangeable positions.

8. Calcium in the lime-treated materials can satisfy the exchange capacity and complex formation of any organics that are present and reduce the formation of gas bubbles, thus controlling to some extent the long-term settlement of the sediments; because of flocculation and cementation effects, a more open and stable structure was formed and the permeability was increased by an order of magnitude relative to the permeability of the untreated materials.

9. The volatile solids contents of the leachates from lime-treated sediments were higher than those of the leachates from untreated samples because of the greater removal of organics from the sediments by calcium ions. Moreover, the sodium, iron, and potassium ion concentrations of the leachates from the treated materials were lower than those from the untreated materials; this may be due to the absorption of those metal ions to the sediment particles. Since lime treatment introduced a larger amount of calcium ions in the leachates, the pH values were increased to about 12 at the beginning of the test.

In summary, the leachates of dredged materials placed with or without chemical additives in diked containment areas do not appear to cause any serious pollution problems; this is due in large part to the fact that (a) the permeability of most clayey silt dredged materials is very low compared with that of sanitary sludge, (b) the soil has the natural ability to remove many contaminants, and (c) the groundwater is able to adequately dilute the relatively small amounts of contaminants that are leached from the solids.

CHAPTER 8

EVAPORATION

Dewatering is one of the more effective procedures for improving the engineering properties of dredged materials, and recent experience (Krizek, Karadi, and Hummel, 1973), suggests that evaporation offers considerable promise for the economical dewatering of such materials. Therefore an experimental investigation of evaporative losses of water from dredged materials, together with the accompanying strength increases, was conducted as part of this research program.

In nature, the direct evaporation of water from the ground surface and the transpiration of water through plants can not be separated. However, the scope of the study presented in this chapter is directed solely toward an evaluation of the effects of direct evaporation from the ground surface, and a discussion of transpiration is presented in Chapter 9.

BACKGROUND AND RELATED WORK

Observations from the Island, Riverside, Penn 7, and Penn 8 disposal sites at Toledo, Ohio, indicate that evaporation effects play an important role in drying and strengthening the top few feet of dredge spoil in landfills. For example, Krizek, Karadi, and Hummel (1973) describe a specific field situation at Riverside Site where the area inside the dike was like a sea of mud in December of 1970, but six months later this area was covered with a dense growth of vegetation from 8 to 10 feet high with lower stems up to an inch in diameter and it could easily be traversed on foot, although most areas were too soft to support any heavy equipment. Despite the fact that these observations do not identify what proportion of the water was lost by evaporation and transpiration and what proportion drained into the underlying soils, the major effect near the surface was undoubtedly due to evaporation and transpiration, since the lower materials still had relatively high water contents.

McNely (1966) discussed field observations and field data for the evaporative drying of San Francisco Bay mud dredged hydraulically from Marina Lagoon and deposited on Mariner's Island. In general, the original depth of freshly deposited slurry was approximately 3 feet, the average dry density of the slurry was on the order of 25 pounds per cubic foot. After seven months the thickness decreased to about half of the original thickness and the dry density doubled. A dry crust approximately 0.2 foot thick and firm enough to support the weight of a man had formed over the hydraulic fill almost everywhere in Area 2, even though there had been much rain during the preceeding two months. Prior to the rain openings were cut in the dike, and these openings apparently allowed most of the rainwater to drain from the fill. Figure 8-1 shows that the shrinkage (or reduction of depth) was on the order of 40 percent after 10 weeks of drying, and 50 percent after 20 weeks of drying.

Table 8-1 summarizes the observations made during field inspections os six hydraulic fill areas on August 30, 1965, November 23, 1965, and January 25, 1966. During the first few weeks of the fill operation there were some indications that the fill might not cover a given

Table 8-1

Field Observations of Evaporation Effects
(After McNely, 1966)

Area	Elapsed Time (weeks)	Depth of Fill (feet)	Depth of Cracks (feet)	Width of Cracks at Top (inches)	Grid Spacing (feet)	Able to Walk on (%)	Covered by Ponds (%)
HF-2	9	1.9	0.5	2	2	5	0
	21	1.5	1.5	3	2	100	0
	30	1.5	1.5	4	1.5	100	0
HF-3	9	1.9	0.4	2	1.5	0	0
	21	1.5	1.0	2	1	100	20
HF-4	5	2.1	0.2	0.5	1	0	5
	18	2.0	1.0	1.5	1.5	50	40
HF-5	5	1.9	0.4	2	1.5	0	5
	17	1.5	1.5	3	1.5	90	5
HF-6A	6	2.1	0.2	0.5	1	0	1
	18	2.0	1.0	1.5	1.5	5	50
HF-6B	6	2.0	0.2	0.5	2	0	5
	18	1.5	1.0	1.5	1	15	25

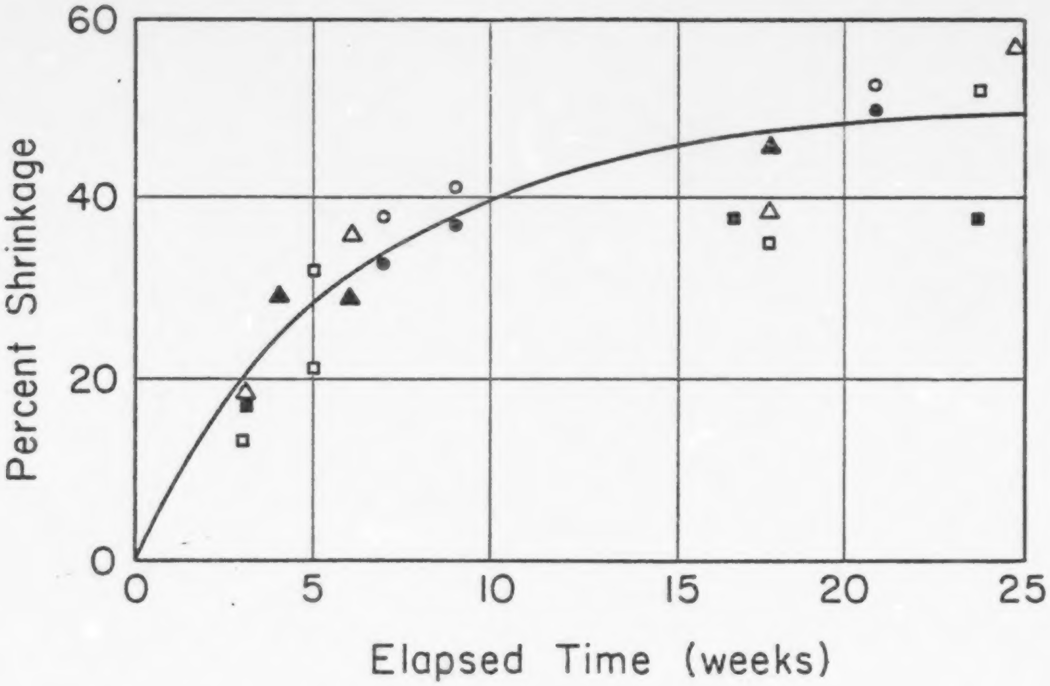


Figure 8-1. Hydraulic Fill Shrinkage versus Time
(After McNely, 1966)

hydraulic fill area uniformly. However, subsequent field observations made as the slurry dried over a period of several months after the fill operation was terminated showed that the thickness of fill was fairly uniform. This may be due to the effect of a mud flow or sediment creep phenomenon. Since the average fill depth seven months after termination of operations was on the order of 1.5 feet, the strength and deformation behavior of the fill may be greatly influenced by the subsurface drainage conditions.

Garbe and Jeno (1968) reported that the results of a field test in which mechanical equipment was used to agitate the dredged materials, thereby accelerating the drying process. This reclamation project involved the use of a hydraulic dredge to fill former tidal marshes with bottom material from the Belmont Slough, and the results collected in a little more than a month are shown in Figure 8-2. A comparison of the final water contents of the non-conditioned materials indicates that the thin lift of 12 inches dried from over 200% water content to about 110%, whereas the thick lift of 48 inches dried to about 170%, thus implying that the evaporation effect on the thinner layer was substantially higher. The conditioning of the material in the 16 inches and 21 inches lifts consisted primarily of manipulating the materials with a dozer. The rate of change of water content was higher for the

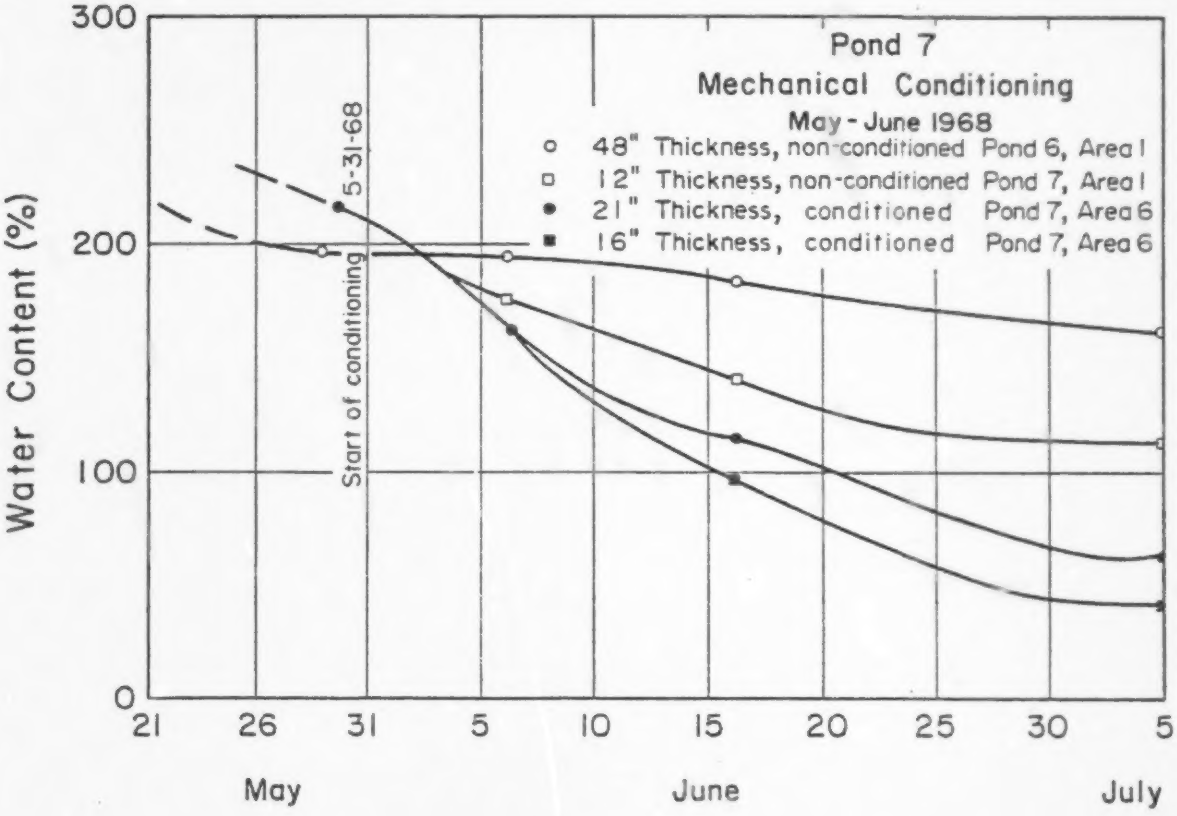


Figure 8-2. Water Content versus Time (After Garbe and Jeno, 1968)

conditioned materials than for the non-conditioned ones, thereby indicating that evaporative water losses are enhanced by mechanical conditioning. The thinner lift of 16 inches was easier to handle and compact than the thicker lift of 21 inches, and it yielded a lower water content (40% compared to about 60%) within the given time period of tests.

Greeley and Hansen (1969) reported the results of a series of laboratory evaporation tests on dredged materials obtained from the Calumet River in Chicago, Illinois. The program consisted of tests to determine the rate of drying of dredgings deposited to depths of 2, 4, 8, and 12 inches, with and without mixing, at a fairly uniform temperature of 74°F and relative humidity of 58%. Mixing (in cases where mixing was part of the test procedure) was done three times per day for the 4-inch and 8-inch samples and at one-hour intervals for the 2-inch sample; the 12-inch samples were not mixed. Figure 8-3a shows that the rate of drying is nearly constant for a given layer thickness and degree of mixing; the thinner lifts dried more quickly than the thicker ones, and the mixed layers dried more quickly than the unmixed ones for each particular thickness. Figure 8-3b demonstrates the increase in drying rates achieved by mixing, and Figure 8-3c illustrates the drying rate of the mixed layers as a percentage of the drying rate for the unmixed layers; it can readily be seen that greater relative effects are accomplished by mixing the thicker layers.

Based on assumptions for the dredging rate, required water content, average climatic conditions, and drying rates determined from laboratory tests, Greeley and Hansen (1969) proposed the construction of drying beds such as those shown in Figure 8-4; the predicted field performance

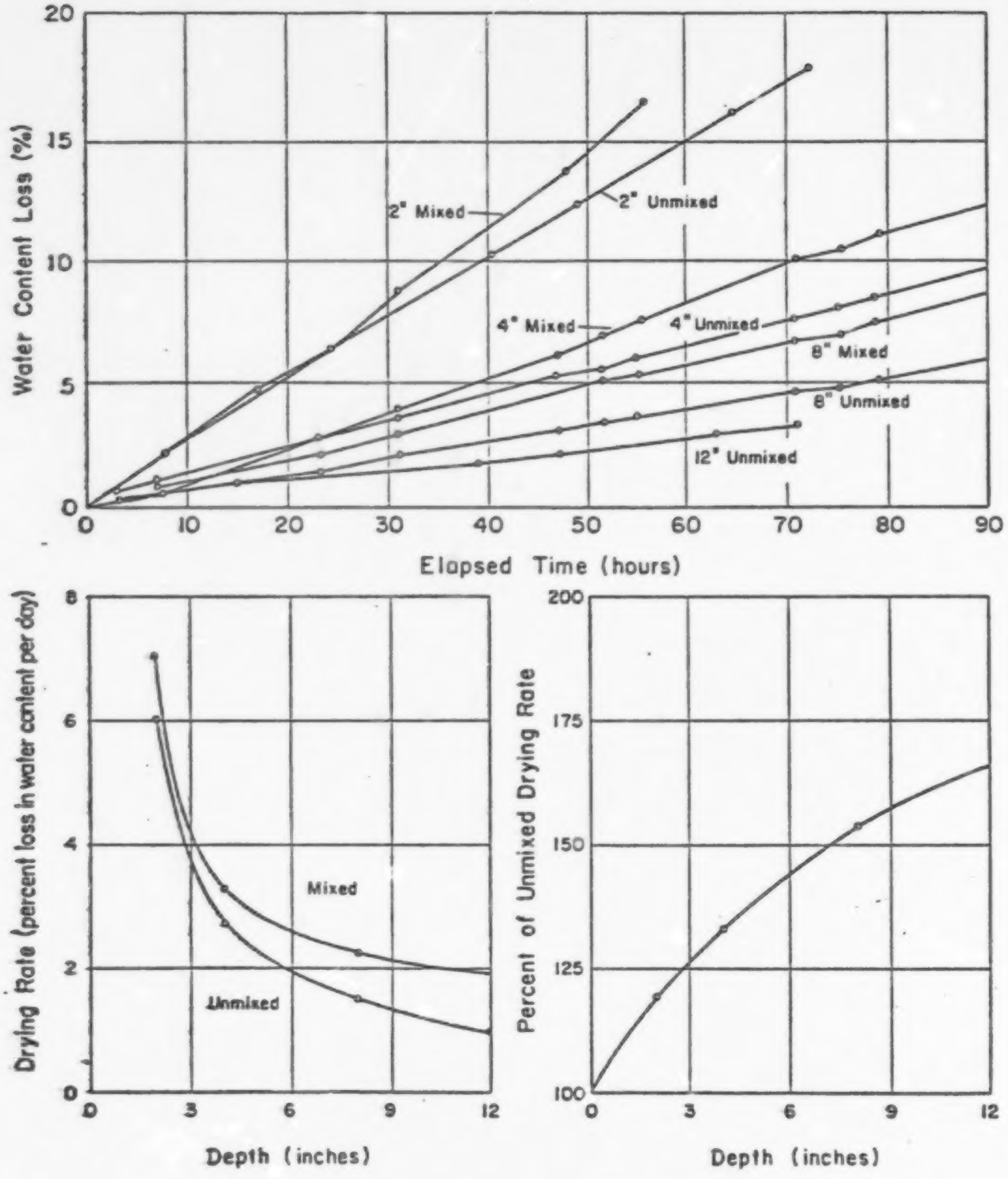


Figure 8-3. Laboratory Study of Evaporation Losses
(After Greeley and Hansen, 1969)

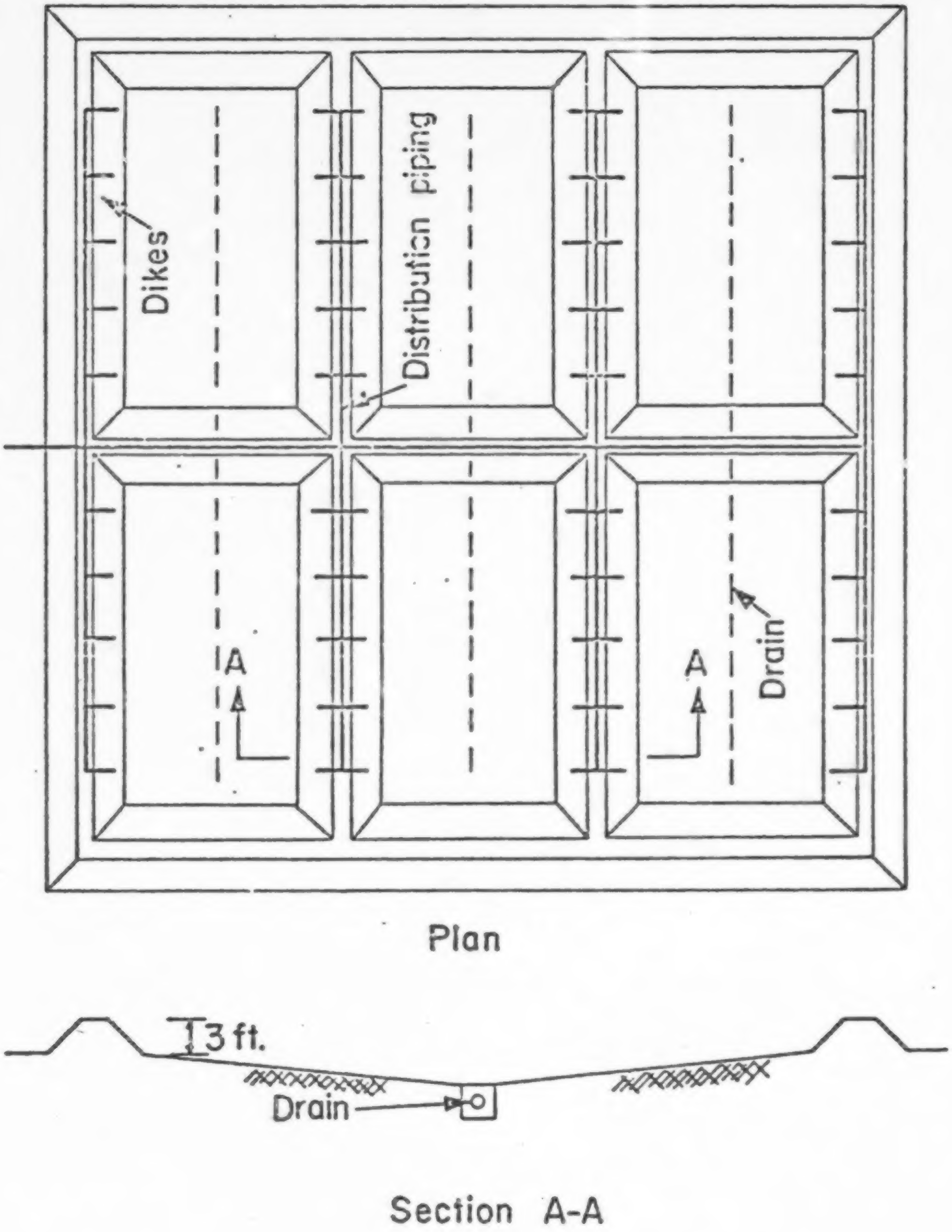

Dikes
Distribution piping
A
A
Drain
Plan
3 ft.
Drain
Section A-A

Figure 8-4. Proposed Scheme of Drying Beds for Dredgings
(After Greeley and Hansen, 1969)

of the drying beds is given in Table 8-2. Based on their economic study, it was estimated that about 100 acres of land would be required to dry 200,000 cubic yards of dredged material per year at a cost of about $1.28 per cubic yard if placed hydraulically, or that about 55 acres of land would be required to dry the material at a cost of about $0.85 per cubic yard if placed by trucks. Costs for the dredging operations or for the movement of the dredgings into and out of the drying areas were not included in these estimates.

Supported by the Office of Dredged Material Research, U.S. Army Engineer Waterways Experiment Station (1974), Dames and Moore conducted a field demonstration of a proposed evaporation methodology at a disposal site near Monroe, Michigan. The field test procedure involved an almost continuous conditioning of a layer of dredged material slurry by a tracked vehicle to accelerate the evaporation of water and to create a layer of relatively dry soil which was then compacted with conventional construction equipment. The 2 acre demonstration site was cleared and the in-situ silty sand was compacted and saturated. A 3-foot high dike was constructed around the site, which was divided into two test areas; Area 1 was 200 feet by 100 feet and Area 2 was 200 feet by 190 feet in size. Also constructed was a control pond where dredged material was deposited and decanted, but not conditioned. Material (described as a dark gray fat clay) dredged from the nearby Raisin River was pumped into the test areas and the control pond to a depth of 20 inches and allowed to settle overnight; then, approximately 2 inches of free water was decanted over weirs in the dike, resulting in an 18 inch layer of slurry. The water contents of the slurry after

Table 8-2

Predicted Field Performance of Drying Beds
(After Greeley and Hansen, 1969)

Depth of fill (inches)	2.0	4.0	8.0	12.0
Drying rate (% per day)	6.0	3.0	1.5	1.0
Filling rate (days per acre)	0.3	0.6	1.3	1.9
Drying time (days)	8.3	16.7	33.3	50.0
Removal rate (days)	0.4	0.7	1.1	1.5
Drying cycle (days)	9.0	18.0	35.7	53.4
Volume (cubic yards per acre)	268	536	1072	1608
Volume (cubic yards per acre per day)	29.8	29.8	29.9	30.1
Area for 2000 cubic yards per day (acres)	67.0	67.0	67.0	67.0
Area required (acres)	141	114	85	63
Application rate (cubic yards per day)	4200	3400	2550	1900

decanting were 245 percent and 386 percent in Areas 1 and 2, respectively. A Caterpillar 977H loader and an Allis-Chalmers D-11 bulldozer, tracked vehicles with 2-inch cleats, were used to condition the slurry; this was accomplished by operating the vehicles with the blade or bucket lowered about 3 inches into the slurry. A Ford 9000 rubber-tired tractor with a rear rake attachment was used for a short time.

The cleats on the tracks of the loader and the bulldozer caused unexpected deterioration of the foundation material and subsequent mixing of the foundation material into the slurry. After 8 days and approximately 250 coverages, conditioning of Area 1 was discontinued because severe foundation deterioration resulted in the miring of equipment. The rubber-tired tractor was used in Area 2 when the water content was about 52 percent, and it worked well until the water content was reduced to about 44 percent (after about 14 hours), at which time the tires could no longer maintain traction. Conditioning of Area 2 was continued with the tracked equipment. However, because of foundation deterioration and inclement weather forecasts, the demonstration was terminated after 30 days of conditioning, even though the water content of the material was not lowered sufficiently to permit compaction with a sheepsfoot roller. Nevertheless, the field test was considered to have successfully demonstrated the effectiveness of this mixing and evaporation concept.

The major findings of this demonstration are illustrated in Figure 8-5. Figure 8-5a shows the reduction in water content as a function of time for the test areas and the control pond. Figure 8-5b gives the water content reduction as a function of coverages in the test areas.

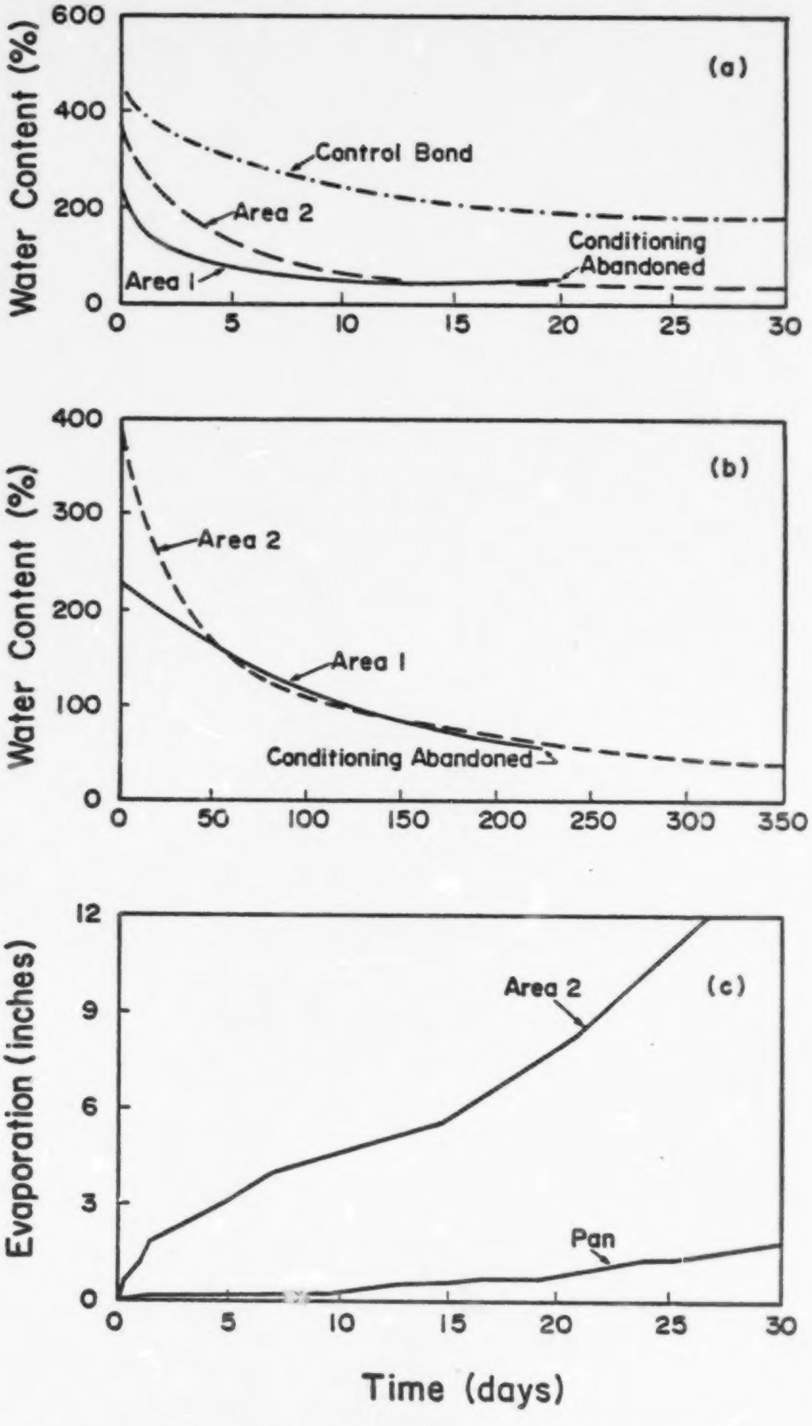


Figure 8-5. Field Study of Evaporation Losses by Conditioning (After Dredged Material Research, 1974)

Figure 8-5c illustrates the rate of evaporation in Area 2 as a function of time and relative to the pan evaporation rate. During this demonstration approximately 3 inches of rain was recorded and there were few days of sunny weather. It should be noted that the mixture of foundation material into the slurry could account for some of the reduction in the water content; in this regard the amount of water per square foot removed from the area was based on water content determinations and the depth to firm foundation material, as measured throughout the test period. Valuable information was also gained on equipment performance. Although tracked vehicles appear suitable for conditioning dredged material placed on fine-grained foundation materials, they certainly are not suitable for operation on sandy materials. Where granular foundation materials exist, rubber-tired vehicles may be satisfactory until the point is reached where they can not maintain traction as the slurry becomes stiffer. If the method were used on a large scale, special equipment, such as marsh buggies or other low ground pressure vehicles, or devices that can be moved through the slurry by cables, may be preferable. At present, concepts are being considered where a containment area would be partitioned into several smaller areas; staged planning would permit filling operations in some of the areas while previously filled areas were being conditioned.

TEST PROCEDURES AND RESULTS

Notwithstanding the findings reported in the test series described above, it was judged desirable to undertake an experimental investigation of evaporative losses in connection with this study, and the results of this test program are given in this chapter; included are specific test sequences dealing with water retention characteristics, laboratory evaporation, and field evaporation.

Water Retention Characteristics

The soil-water potential of dredged materials was studied to obtain a better understanding of the material behavior during the evaporation process. Slurry specimens were thoroughly mixed, placed into small (1.7 inches in diameter and 2.5 inches in height) permeameters, and allowed to settle (with vertical drainage) for two or three days until an equilibrium state was reached. The final sediments averaged 1.6 inches in height and were nearly saturated. Because of the difficulty in handling the soft sediments, each specimen was underlain by a cellulose acetate membrane (2.5 inches in diameter by 0.13 inches thick) and transferred into a 15-bar ceramic plate extractor (Richard, 1965). The desorption scheduled followed was 1/10 bar, 1/3 bar, 2/3 bar, 1 bar, 2 bars, 5 bars, 10 bars, and 15 bars. The water content of each specimen was measured at various pressures, and the dimensions of each specimen was measured at the initial and final stages. The water retention curves for these specimens are presented in Figure 8-6, and the volume of contraction, estimated void ratio, and estimated degree of saturation at the initial state and after 10 bars and 15 bars of pressure are presented in Table 8-3.

During the conduct of these tests it was difficult to determine when equilibrium was attained for each pressure increment, especially for pressures greater than 5 bars. The larger pressures were maintained for as long as 45 days in an attempt to ensure that the specimens reached equilibrium. Figure 8-7 shows plots of water content versus the

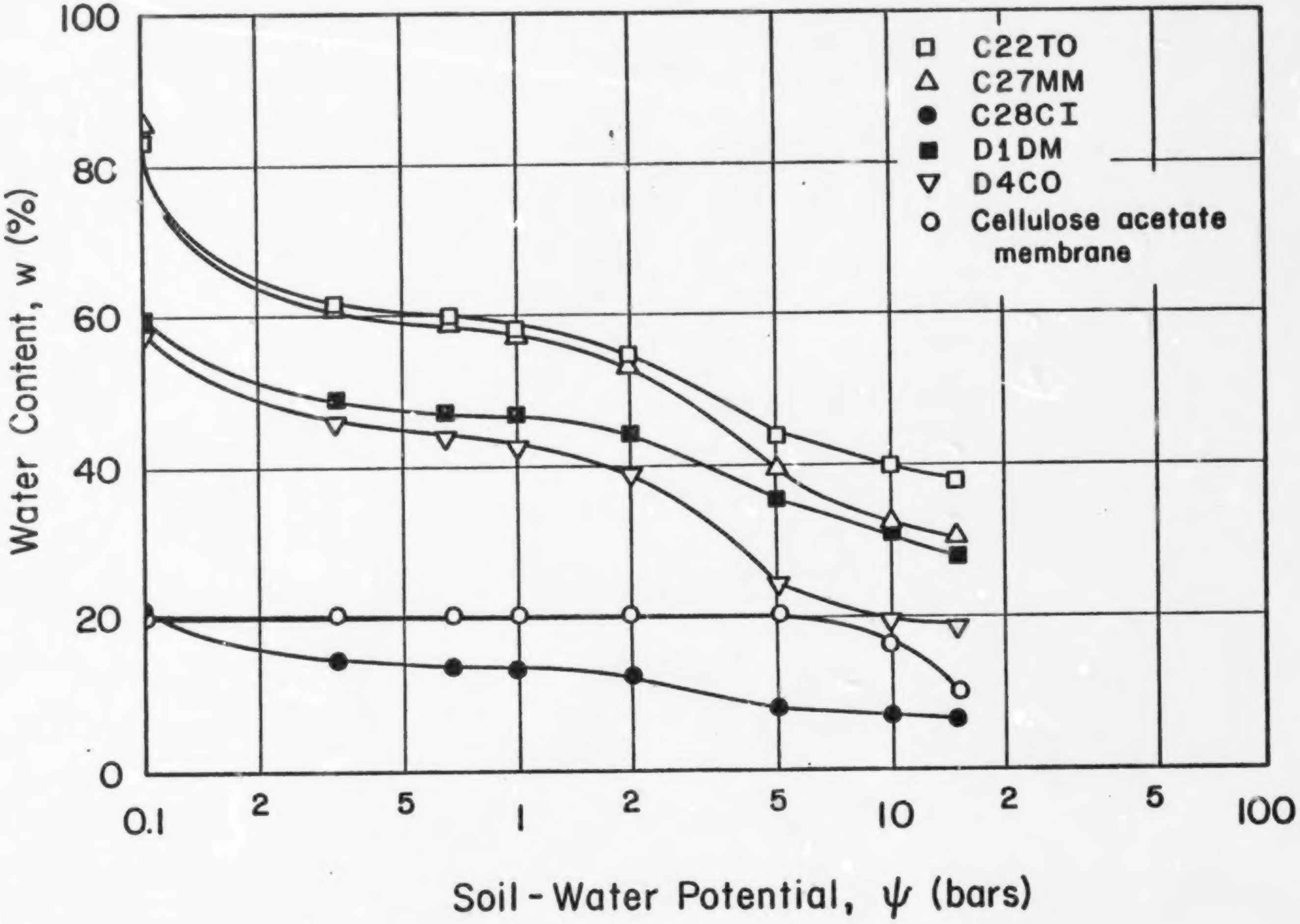


Figure 8-6. Characteristic Water Retention Curves

Table 8-3

Volume of Contraction, Estimated Void Ratio, and Estimated Degree of Saturation after Applied Suction of 10 and 15 Bars

		C22TO	C22TO	C27MM	C27MM	C28CI	C28CI	DIDM	DIDM	D4CO	D4CO
Volume (cm^3)	Original	60.1	64.6	61.4	61.9	68.9	68	59.7	63.7	53.6	47.1
	After 10 Bars	42.9		41.8		65.1		47.0		38.2	
	After 15 Bars		43.9		36.7		63.7		46.7		32.9
Volume of Contraction (%)	After 10 Bars	28.7		31.9		5.5		21.3		28.7	
	After 15 Bars		32.0		40.7		6.3		26.6		30.2
Estimate* of Void Ratio	Original	1.96	2.15	2.23	2.58	0.71	0.88	1.97	1.99	1.85	1.81
	After 10 Bars	1.11		1.20		0.62		1.34		1.03	
	After 15 Bars		1.14		1.12		0.76		1.19		0.96
Estimate* of Degree of Saturation (%)	Original	126	113	114	93.7	84.8	82.4	85	80.4	91.5	81.9
	After 10 Bars	97.7		81		33.4		66.2		55.3	
	After 15 Bars		87.7		67.9		20.2		58.4		46.4

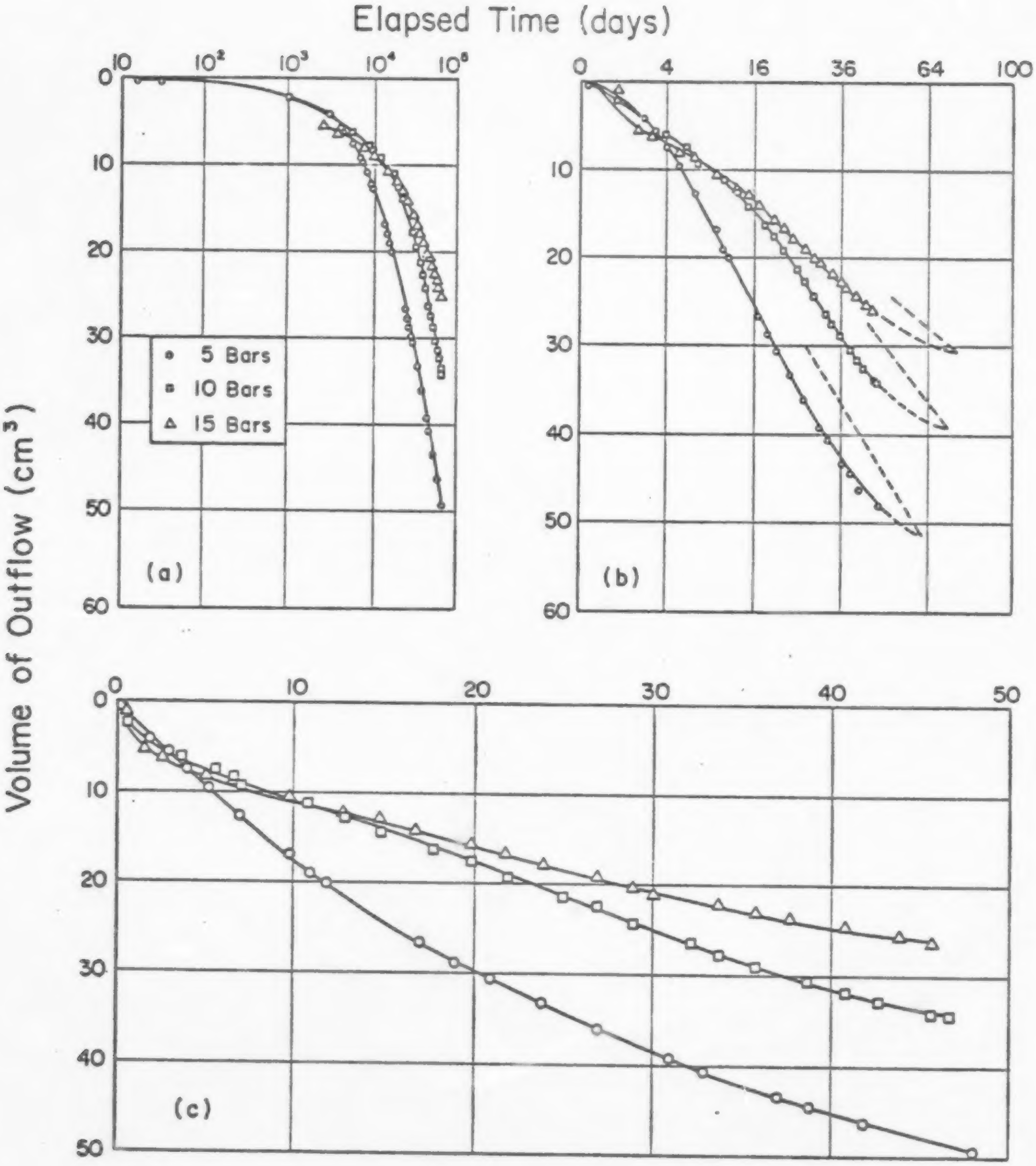


Figure 8-7. Extractor Outflow versus Time Curves

logarithm of time, the square root of time, and arithmetic time, but none of the plots yielded a satisfactory criterion for determining when equilibrium would be reached. However, engineering judgement suggests that maintaining pressures for longer times would not proportionately improve the characteristics of the water retention curves. According to Klute (1965), the time required for 99 percent of the water loss to occur is

$$t_{99} = 1.68\ h^2/D \quad , \tag{8-1}$$

where h is the specimen height and D is the diffusivity, which will probably be in the range of 10^{-5} to 10^{-1} cm^2 per sec for most soils. If the minimum diffusivity is chosen, the time required for 99 percent of the outflow to occur under a given pressure is about 30 days. Therefore, the 45 days allowed for equilibrium appears to be justified for practical purposes. The shape of the water loss curves obtained reflects the peculiar secondary consolidation behavior of these organic dredged materials (Krizek and Salem, 1974). Visible cracks were not observed in the specimens after pressures of 15 bars. After pressures of 2 bars, cracks were found between the specimens and the cellulose acetate membrane.

Laboratory Evaporation

In this test program three series of tests were conducted. Different parameters were studied in each series, and the results obtained in the earlier series were used in planning subsequent tests. The purposes of the first series of laboratory evaporation tests were to study the rate of water loss from dredged materials obtained from several different disposal sites and to determine the effect of the mixing on this rate. Each of seven materials was thoroughly mixed and poured into two identical glass containers (6 inches in diameter and 6 inches in height) to the same depth. All tests were conducted under the same conditions of temperature (72°F), atmospheric pressure (1 atmosphere),and relatively humidity (30%). For each material one container was left undisturbed while the other was mixed once daily by a paddle stirrer.

Tables 8-4 and 8-5 summarize the changes in average water contents and sample thicknesses with time, and Figure 8-8a shows a typical plot of the change in water content as a function of time. Similar plots (not shown) for the data in Table 8-4 indicated that the water content varied linearly with time up to about 25 days, after which the rate decreased, as shown in Figure 8-8a. The slope of the linear portion is a measure of the initial rate of water loss due to evaporation; this initial rate of water loss increased with increasing initial water content and decreased with increasing clay content. It was found that there was no significant different in the rates of water loss for the mixed and unmixed samples; this may be due to the infrequent mixing and the high initial water contents of the samples. With more frequent mixing, Greeley and Hansen (1969) found significant increases in the rates of water loss due to mixing in the laboratory (Figure 8-3a). The field tests of Waterways Experiment Station, U.S. Army Engineer (1974) also resulted in a significant increase in the rate of water loss with mixing (Figure 8-5a). The volume change data presented in Table 8-5 did not show any general trends.

The purposes of the second series of laboratory evaporation tests were to study the influence of sample thickness and surface area on the rate of water loss, to observe crack sizes and patterns, and to determine

Table 8-4

Time-Dependent Decrease in Average Water Content for Jar Samples Tested in First Series of Laboratory Evaporation Tests

Elapsed Time (days)		0	1.5	7	17	40	45	58	63	73
C22TO	Unmixed	182	175	147	89	10.4	6.6	2.9		
	Mixed	173	162	131	74	5.3	4	2.6		
C27MM	Unmixed	158	149	124	71	10.6	7.4	2.8		
	Mixed	149	140	117	73	10.1	6.5	3.0		
C28CI	Unmixed	42	40	33	18.5	5.2	4.3	2.6		
	Mixed	37	35	28	15	3.3	2.7	1.6		
C80TO	Unmixed	218	214	194	151	58	38	3.5	2.2	2.2
	Mixed	192	184	166	128	65	48	10.4	6.1	3.9
	Unmixed	200	191	170	135	59	54	7.2	4.0	3.0
	Mixed	190	184	168	133	66	53	15.2	7.9	4.4
DIDM	Unmixed	104	99	88	64	24	19	9.4	7.5	6.0
	Mixed	102	98	89	69	30	23	11.5	9.5	7.7
D3TO	Unmixed	169	160	144	105	40	28	4.2	2.7	2.7
	Mixed	146	141	129	103	47	37	9.6	4.6	3.9
D4CO	Unmixed	97	93	81	59	21	16	6.2	4.4	3.3
	Mixed	93	90	80	60	20	15.4	6.9	4.8	3.4

Table 8-5

Time-Dependent Decrease in Sample Thickness for Jar Samples Tested in First Series of Laboratory Evaporation Tests

Elapsed Time (days)		0	1.5	7
C22TO	Unmixed	4.60	4.45	3.95
	Mixed	4.60	4.48	3.90
C27MM	Unmixed	3.70	3.60	3.25
	Mixed	3.70	3.47	3.05
C28CI	Unmixed	4.00	3.80	3.61
	Mixed	3.90	3.73	3.56
C80TO	Unmixed	4.25	4.20	4.00
	Mixed	4.45	4.45	4.00
	Unmixed	4.30	4.27	4.05
	Mixed	4.50	4.30	3.95
DIDM	Unmixed	4.00	4.00	3.70
	Mixed	3.95	3.90	3.68
D3TO	Unmixed	4.20	4.20	4.05
	Mixed	4.20	4.15	3.90
D4CO	Unmixed	4.50	4.35	3.85
	Mixed	4.60	4.50	4.05

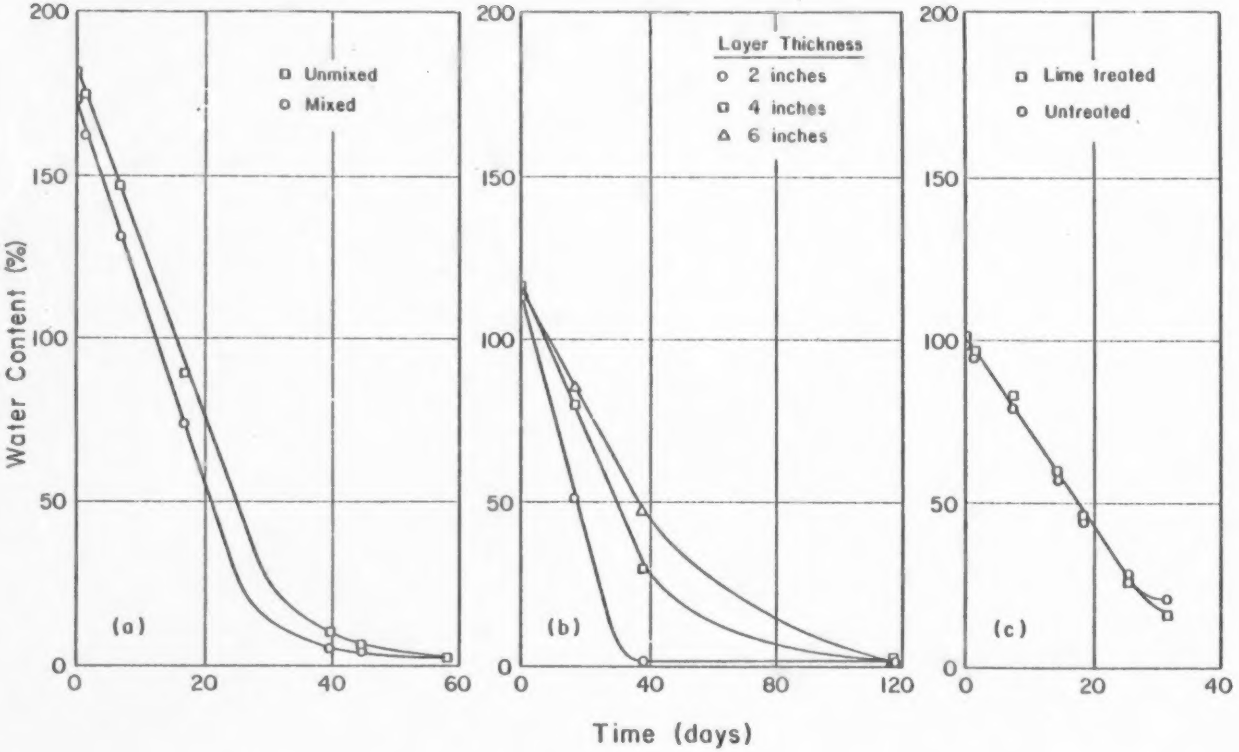


Figure 8-8. Typical Laboratory Evaporation Rates for Various Conditions

the shear strengths of the drying soils. Each material was thoroughly mixed and poured into glass jars (6 inches in diameter by 6 inches high) to depths of 2, 4, and 6 inches. Another sample of each material was placed in a plastic pan (18 inches long by 13 inches wide) to a depth of 3.5 inches. All samples were allowed to dry without mixing, and periodic measurements of water content, sample thickness, crack widths, and shear strength were made. These tests were conducted at a temperature of 78°F, an atmospheric pressure of 29.5 inches of mercury, and a relative humidity of 55%. Table 8-6 presents the variations of average water content, sample thickness, vane strength, and cone strength with time for the 21 specimens in glass jars. Table 8-7 presents the variations of average water content, sample thickness, width of cracks, vane strength, and cone strength with time for the 8 specimens in plastic pans. Figure 8-8b shows typical plots of water content versus time for jar samples. Again, the slopes of these curves were constant at the beginning of the test period. Similar plots (not presented) for the other jar and pan samples showed that higher initial water losses occurred in the thinner specimens and that the initial rates of water loss increased with increasing initial water contents.

Shear strengths increased rapidly with drying, and after about 40 days strengths were greater than the measuring capacity of the equipment used. A discussion of shear strength, deformation, and cracking will be deferred until after the presentation of data for the remaining laboratory and field evaporation tests.

The purposes of the third series of laboratory evaporation tests were to study the effect of lime $Ca(OH)_2$ on the water losses, shear

Table 8-6

Time-Dependent Variations of Average Water Content, Sample Thickness, Vane Strength, and Cone Strength for Jar Samples Tested in Second Series of Laboratory Evaporation Tests

Time (days)	Variable	C22TO			C27MM			C28CI			C80TO			D1DM			D3TO			D4CO		
0	Water Content (%)	112	116	114	127	125	125	28.1	27	19.8	142	125	128	79	80	78	91	93	94	79	83	83
	Thickness (in.)	2.2	3.9	6	1.8	3.9	6	2.4	4.35	5.9	2.1	4.35	6	2.35	4.1	6	2.1	4.1	5.95	2.1	4.35	5.95
	Vane Strength (psf)																					
	Cone Strength (psf)																					
17	Water Content (%)	50.7	80.4	84.5	50	89.4	95	6	14.3	7.8	78.4	95	98.4	38.4	55	57.1	47.6	69	71.7	35.5	59.6	61.5
	Thickness (in.)	1.7	3.3	5.3	1.52	3.3	5.25	2.15	3.9	5.85	1.6	3.6	5.1	2	3.5	5.25	1.7	3.5	5.15	1.7	3.8	5.5
	Vane Strength (psf)	890	92	53	1250	60	38	2430			205	21	30	1835	275	183	900	102	101	1715	74	72
	Cone Strength (psf)	3480	550	550	3870	230	92	5040	4700	4650	680	77	118	5040	645	600	3670	610	600	4450	310	145
38	Water Content (%)	1.4	30.3	47.5	1.8	32	59	1.1	3.2	3.4	11.7	44.2	57	4	15.8	26	2.3	24.4	38.5	2.2	20.2	268
	Thickness (in.)	1.55	2.9	5.1	1.3	2.8	4.55	2.15	3.85	5.85	1.45	3.1	4.4	1.9	3.4	5.1	1.55	3.1	4.55	1.7	3.55	4.9
	Vane Strength (psf)			980			740					1133	354						2300			
	Cone Strength (psf)		5830	4650		5750	3490		6020			3490	2460			5750		6150	4850		6020	5500
110	Water Content (%)	1.4	1.5	1	0.9	0.8	0.9	0.6	0.4	0.2	1.3	0.7	1.7	1	1.2	1.2	1.2	1.2	1.3	1.1	1.1	2
	Thickness (in.)	1.55	2.9	4.1	1.3	2.8	4.1	2.15	3.85	5.85	1.45	3	3.8	1.9	[illegible]	5.05	1.55	3.10	4.45	1.7	3.55	4.55
	Vane Strength (psf)																					
	Cone Strength (psf)																					

Table 8-7

Time-Dependent Variations of Average Water Content, Sample Thickness, Width of Cracks, Vane Strength, and Cone Strength for Pan Samples Tested in Second Series of Laboratory Tests

Time (days)	Variable	C22TO	C27MM	C28CI	C80TO	DIDM	D3TO	D4CO	D3TO with 3% Ca(OH)$_2$
0	Water Content (%)	99.0	79.0	20.2	49	82.9	100.4	80.6	89
	Thickness (in.)	2.25	1.95	3	1	2.75	3.15	3.25	3.2
	Crack Width (in.)								
	Vane Strength (psf)								
	Cone Strength (psf)								
15	Water Content (%)	73.6	56.5	9.75	13.6	66.2	73.3	56.3	69.1
	Thickness (in.)	2.05	1.87	3	0.95	2.6	2.75	3.02	3.02
	Crack Width (in.)	0.15-0.30	0.17		0.25-0.65				0.40
	Vane Strength (psf)	218	315						147
	Cone Strength (psf)	630	940	4650	4060				280
24	Water Content (%)	54.2	38.2	6.3		38.8	54.7	43.2	46.2
	Thickness (in.)	2.03	1.86	3		2.5	2.25	2.9	2.7
	Crack Width (in.)					0.13-0.50	0.13-0.38	0.25-0.44	
	Vane Strength (psf)					3365	330	1310	
	Cone Strength (psf)					5050	1245	4260	
48	Water Content (%)	5.16	3.56	4.55		6.75	8.05	8.66	4.7
	Thickness (in.)	2	1.85	3		2.45	2.2	2.8	2.55
	Crack Width (in.)	0.38-0.88	0.50-1	No big cracks		0.38-0.63	0.50-1.13	0.38-0.63	0.50-1
	Vane Strength (psf)								
	Cone Strength (psf)								
120	Water Content (%)	2.06	1.97	0.60	2.07	1.98	1.85	1.78	1.54
	Thickness (in.)	2	1.85	3		2.45	2.2	2.80	2.5
	Crack Width (in.)	0.38-0.88	0.50-6	No big cracks		0.38-0.63	0.50-1.13	0.38-0.63	0.50-1
	Vane Strength (psf)								
	Cone Strength (psf)								

strength, deformation, and crack pattern of the sediment, to obtain additional data to help in interpreting results of the previous laboratory evaporation test series, and to serve as a guideline for the interpretation of field evaporation test data. The sample preparation and test procedures were essentially the same as used for the second laboratory test series. Lime was added (3% of the dry weight of the solids) to one-half of the test samples before mixing. Tests were conducted at a temperature of 76 ± 6°F, an atmospheric pressure of 29.3 ± 0.3 inches of mercury, and a relative humidity of 30 ± 4%.

The average water content, cone strength, and crack width of the jar specimens are presented in Table 8-8, and a typical average water content versus time curve with and without lime treatment is presented in Figure 8-8c. The sample thickness and the cone shear strengths for the jar samples are given in Figures 8-9 In these figures, the upper, nearly horizontal, curve records the thickness of the specimen versus time, and the lower, nearly vertical, curves give the vane shear strength versus depth; the symbols denoting data points on the strength curves correspond to the time for the same symbol on the sample thickness curve (e.g. the strength curve through the circles gives the shear strengths at various depths after 15 days).

Tables 8-9 and 8-10 present the variation of the average water content, sample thickness, vane and cone strengths, and crack widths with time for the 10 pan specimens. In general, the results show that the addition of lime to the materials does not change the initial rate of water loss, but it does reduce the final rate. The addition of lime increases greatly the shear strength gain with time.

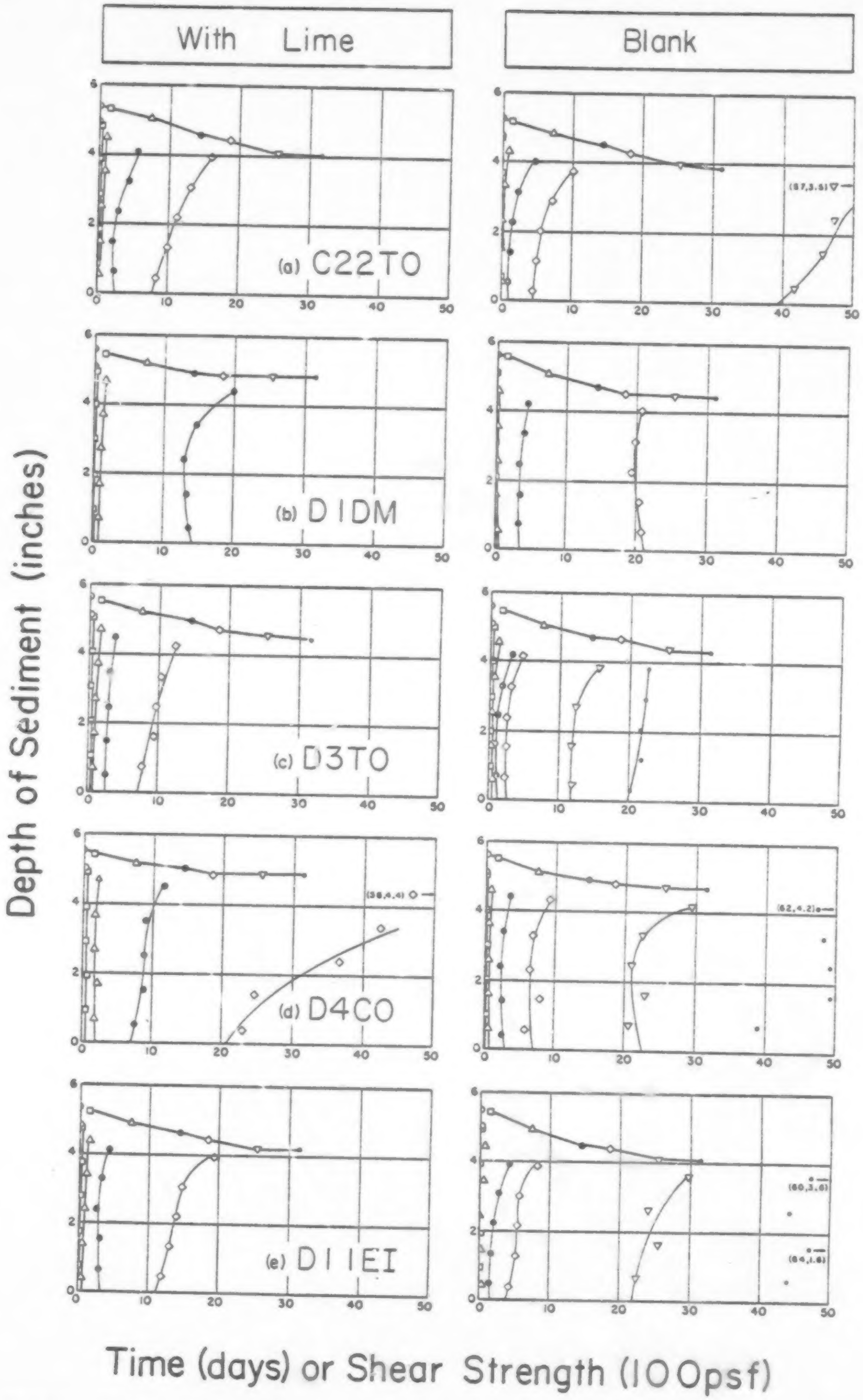


Figure 8-9. Time-Dependent Variations in Sample Thickness and Vane Shear Strength for Jar Samples Tested in Third Series of Laboratory Evaporation Tests

Table 8-8

Time-Dependent Variations of Average Water Content, Cone Strength, and Width of Cracks for Jar Samples Tested in Third Series of Laboratory Evaporation Tests

Time (days)	Variable	C22TO with 3% $Ca(OH)_2$	C22TO Blank	C80TO Blank	DIDM with 3% $Ca(OH)_2$	DIDM Blank	D3TO with 3% $Ca(OH)_2$	D3TO Blank	D4CO with 3% $Ca(OH)_2$	D4CO Blank	D11EI with 3% $Ca(OH)_2$	D11EI Blank
0	Water Content (%)	101.5	99	102	76.9	83.9	87.3	91.2	61.8	70	85	89.5
	Cone Strength (psf)	18	15	13	16	6	19	18	18	12	17	13
	Crack Width (in.)											
1.5	Water Content (%)	97	94.8	97.9	73.2	80	83.4	87.5	58.8	67	80.4	85.7
	Cone Strength (psf)	82	42	16	84	14	91	84	84	16	91	24
	Crack Width (in.)	0.008	0.008	0.006	0.004	0.003	0.010	0.010	0	0	0.012	0.004
7.5	Water Content (%)	83.4	79.3	82.9	62	66.8	70.2	73.6	47.8	55.8	65.5	72.4
	Cone Strength (psf)	480	546	414	500	90	578	720	512	389	588	560
	Crack Width (in.)	0.3[illegible]0	0.188	0.188	0.125	0.063	0.250	0.250	0.125	0.125	0.188	0.063
14.5	Water Content (%)	60.6	57.5	60.5	45	48.9	59.2	61.1	39	45	52.4	54.3
	Cone Strength (psf)	1630	1710	8[illegible]	1338	1025	1120	980	2030	760	1525	1685
	Crack Width (in.)	0.400	0.250	0.250	0.313	0.071	0.250	0.250	0.188	0.188	0.25	0.25
18.5	Water Content (%)	46.5	44.6	47	31.8	38	47	51.9	29.4	38.1	38.3	46.6
	Cone Strength (psf)	3830	2700	2850	5120	4260	3870	2300	5050	2390	4100	2300
	Crack Width (in.)	0.563	0.313	0.375	0.375	0.250	0.375	0.250	0.25	0.188	0.438	0.375
25.5	Water Content (%)	26.3	28.5	29.4	16.5	21.8	28.5	39.8	19.1	28.1	17.3	34.8
	Cone Strength (psf)	5750	5310	5050	5900	5830	5510	3800	5950	4650	6150	4800
	Crack Width (in.)	0.625	0.500	0.500	0.375	0.250	0.563	0.313	0.25	0.188	0.5	0.5
31.5	Water Content (%)	16.2	20.7	21.4	12.4	16.2	19.7	34.3	14	23.1	10.7	27.6
	Cone Strength (psf)			5670				4730		5120		5360
	Crack Width (in.)	0.625	0.500	0.500	0.375	0.250	0.563	0.313	0.25	0.188	0.5	0.5

Table 8-9

Time-Dependent Variations of Average Water Content, Sample Thickness, and Vane Strength for Pan Samples Tested in Third Series of Laboratory Evaporation Tests

Time (days)	Variable	DIDM Blank	DIDM Blank	DIDM with 3% $Ca(OH)_2$	D3TO Blank	D4CO Blank	D4CO Blank	D4CO with 3% $Ca(OH)_2$	D11EI Blank	D11EI Blank	D11EI with 3% $Ca(OH)_2$
0	Water Content (%)	77.4	74.5	72.4	95.5	71.6	71.5	65	78	84.8	86
	Thickness (in.)	3.4	3.25	2.95	3.1	3.35	3.05	2.8	3.05	3	3
	Vane Strength (psf)			34				49			20
5	Water Content (%)	65.7	63	59.[illegible]	81.2	60.4	62.2	48.9	65.4	68	64
	Thickness (in.)	3.18	3.05	[illegible]	2.9	3.13	2.87	2.7	2.88	2.83	2.85
	Vane Strength (psf)			[illegible].0				375.0			114
10	Water Content (%)	53.7	52	44.6	68.2	48.6	51.7	39.8	52.2	51.1	45.1
	Thickness (in.)	3.05	2.85	2.6	2.7	2.9	2.7	2.6	2.7	2.65	2.55
	Vane Strength (psf)	472	350	1293	198	537	214	2067	542	467	1022
13	Water Content (%)	47	44.7	36	60.4	42.3	46.2	30	44.8	43	32.4
	Thickness (in.)	2.8	2.82		2.6	2.75	2.67		2.7	2.45	
	Vane Strength (psf)	873	1027		367	1148	587		661	1011	
18	Water Content (%)	34.4	31.2	22.3	44.2	29.6	34	17	30	26.2	18.3
	Thickness (in.)	2.8	2.78	2.5	2.55	2.75	2.55	2.55	2.6	2.37	2.45
	Vane Strength (psf)	4437	5320	-	1717	3543	2897		3767	4997	
24	Water Content (%)		18.4	11	27.7		20.7	9.4	15		9
	Thickness (in.)		2.75	2.48	2.55		2.55	2.53	2.55		2.42
	Vane Strength (psf)										
36	Water Content (%)		16.9	3.8	17		14	3.6	10		3
	Thickness (in.)		2.72	2.45	2.5		2.53	2.5	2.45		2.4
	Vane Strength (psf)										

Table 8-10

Time-Dependent Variations of Average Water Content, Cone Strength, and Width of Cracks for Pan Samples Tested in Third Series of Laboratory Evaporation Tests

Time (days)	Variable	D1DM Blank	D1DM Blank	D1DM with 3% $Ca(OH)_2$	D3TO Blank	D4CO Blank	D4CO Blank	D4CO with 3% $Ca(OH)_2$	D11EI Blank	D11EI Blank	D11EI with 3% $Ca(OH)_2$
0	Water Content (%)	77.4	74.5	72.4	95.5	71.6	71.5	65	78	84.8	86
	Cone Strength (psf)			80				89			76
	Crack Width (in.)										
5	Water Content (%)	65.7	63	59.4	81.2	60.4	62.2	48.9	65.4	68	64
	Cone Strength (psf)			611				825			572
	Crack Width (in.)			0.2				0.2			0.4
10	Water Content (%)	53.7	52	44.6	68.2	48.6	51.7	39.8	52.2	51.1	45.1
	Cone Strength (psf)	1350	1380	3520	830	1390	700	3660	1480	1910	2180
	Crack Width (in.)	0.2	0.4	0.15-0.3	0.10	0.4	None	0.15-0.3	0.35	0.4	0.05-0.7
13	Water Content (%)	47	44.7	36	60.4	42.3	46.2	30	44.8	43	32.4
	Cone Strength (psf)	2365	2075		1450	2520	1530		1745	2125	
	Crack Width (in.)	0.33	0.5		0.2	0.55	0.25		0.55	0.75	
18	Water Content (%)	34.4	31.2	22.3	44.2	29.6	34	17	30	26.2	18.3
	Cone Strength (psf)	5130	5130	5120	4180	5040	5040	5600	4970	4970	5440
	Crack Width (in.)	0.15-0.55	0.25-0.70	0.30-0.5	0.30-0.7	0.65	0.25-0.65	0.3-0.4	0.7	0.7-1.1	0.3-0.9
24	Water Content (%)		18.4	11	27.7		20.7	9.4	15		9
	Cone Strength (psf)										
	Crack Width (in.)		0.45-0.8		0.75-1		0.35-0.75		0.5-0.9		
36	Water Content (%)		16.9	3.8	17		14	3.6	10		3
	Cone Strength (psf)										
	Crack Width (in.)										

Field Evaporation

The purpose of the field evaporation test program was to study the strength and deformation behavior of dredged materials, under the climatic conditions at the Penn 7 disposal site in Toledo, Ohio. Field model tests were used rather than full scale field tests to achieve better control of some significant parameters,such as the sediment thickness, drainage conditions, and degree of lime treatment. Twelve gasoline drums (22.5 inches in diameter by 35 inches in height) were used; several had perforated bottoms and a sand layer to allow drainage during the tests, which were begun on August 1, 1973, and continued for 14 days. The temperature during the tests was 71 ± 12°F, the average atmospheric pressure was 29.3 inches of mercury, the average relative humidity was 76%, and the total rainfill was 0.8 inches.

Table 8-11 presents the initial and final conditions of the material. As would be expected, the drained samples consolidated more than the undrained samples, and they therefore exhibited greater final shear strengths. Because of more complete consolidation, the drained samples with the smallest initial height had the greatest shear strengths. Strengths for undrained samples were essentially the same, regardless of initial slurry depth and lime treatment. For the drained samples, lime treatment resulted in lower shear strengths, apparently due to a lesser degree of consolidation of the treated samples during the test period.

A second series of field evaporation tests was conducted at the same site, but with greater sample depths and a longer test period of 113 days (August 15 through December 5, 1973). The temperature during the tests

Table 8-11

Test Conditions and Results from First Series of Field Evaporation Tests

Drum Number	1	2	3	4	5	6	7	8	9	10	11	12
Drainage Condition	Undrained	Drained	Undrained	Drained	Undrained	Drained	Undrained	Drained	Undrained	Drained	Undrained	Undrained
Treated Condition	No	No	No	No	No	No	2% $Ca(OH)_2$	2% $Ca(OH)_2$	4% $Ca(OH)_2$	4% $Ca(OH)_2$	No	No
Initial Depth of Slurry (in.)	2.75	2.75	5.5	5.5	8.25	8.25	5.5	5.5	5.5	5.5	5.5	5.5
Final Depth of Supernatant (in.)	0.5		2.5		4		1.75		1.5		2.5	2.5
Final Depth of Sediment (in.)	1	0.75*	2.75	2	4.25	3.75	4.5	4	4	3.63	3.0	2.75
Vane Shear Strength of Sediment (psf)	28.8	*	28.8	72.2	28.8	57.6	28.8	43.2	28.8	43.2	28.8	28.8

*The sediment is totally dried, the shear strength cannot measure.
Sample Number C120TO
August 1, 12:00 A.M., 1973; Test Begin
August 14, 16:30 P.M., 1973; Data Taken and Test End.

was 58.3 ± 16.4°F, the average atmospheric pressure was 29.3 inches of mercury, and the average relative humidity was 70%. Precipitation during the test period totaled 8 inches and is recorded in Figure 8-10.

Data on test conditions and crack formation are given in Table 8-12. In general, for the drained condition, the thinner specimens developed wider and deeper cracks during drying. This may be due to the higher thermal gradient causing a higher rate of water loss. Lime treatment resulted in fewer, but larger, cracks in the drained samples. Except for the thinnest sample, no cracks formed in the undrained sediments.

Figure 8-11 shows the variation of specimen thickness and shear strength with time. In these figures, as before, the upper, nearly horizontal, curve records the thickness of the specimen versus time, and the lower, nearly vertical, curves give the vane shear strength versus depth; the symbols denoting data points on the strength curves corresponds to the time for the same symbol on the sample thickness curve (e.g. the strength curve through the circles gives the shear strength at various depths after 15 days). Under undrained conditions, lime treatment resulted in low shear strengths in the upper portions of the samples, and, in general, strengths were less than for untreated samples at all depths. For drained conditions lime treatment resulted in lower strengths than for untreated materials. However, on rewetting due to rain, the strengths of untreated samples decreased (in upper portions of the sample), while the strengths of treated samples continued to increase.

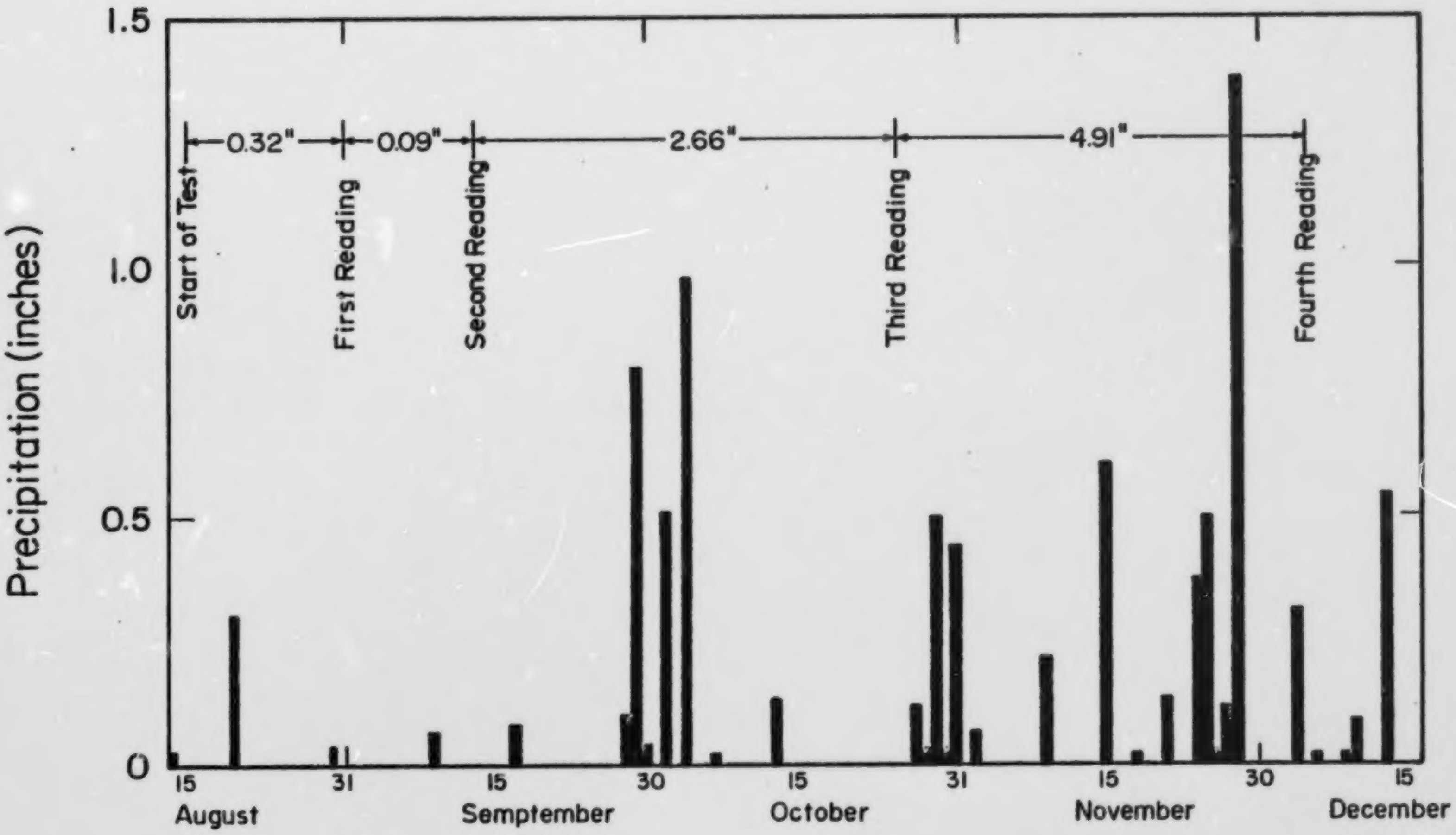


Figure 8-10. Precipitation Record During Second Series of Field Evaporation Tests

Table 8-12

Test Conditions and Crack Patterns from Second Series of Field Evaporation Tests

Drum Number			1	2	3	4	5	6	7	8	9	10
Drainage Condition			Undrained	Drained	Undrained	Drained	Undrained	Drained	Undrained	Drained	Undrained	Drained
Treated Condition			None	None	None	None	None	None	2% $Ca(OH)_2$	2%$Ca(OH)_2$	4% $Ca(OH)_2$	4% $Ca(OH)_2$
Average Thickness (in.)			5.6	4.4	11.9	7.6	19.7	14.7	12.8	8.8	11.7	10
August 15, 1973 Test Started	0 day	Width of Crack (in.)										
		Depth of Crack (in.)										
August 30, 1973 Syphoned out Supernatant	15 days	Width of Crack (in.)										
		Depth of Crack (in.)										
Sept. 13, 1973	29 days	Width of Crack (in.)	0.5	1.5		0.5		0.5		0.5		0.5
		Depth of Crack (in.)	2.5	To Bottom		1.5		1.5		1.5		1.5
Oct. 25, 1973	71 days	Width of Crack (in.)	0.3-0.7	0.7-1.5		0.3-1		0.4-0.6		0.3-1		0.7-1.5
		Depth of Crack (in.)	3	To Bottom		1.7		1.0-1.7		2.3		2.5
Dec. 5, 1973	113 days	Width of Crack (in.)	0.5-1	1		0.7		0.5		0.5-1		1-1.3
		Depth of Crack (in.)	To Bottom	To Bottom		1.5-2		1-1.5		2		1.5-2

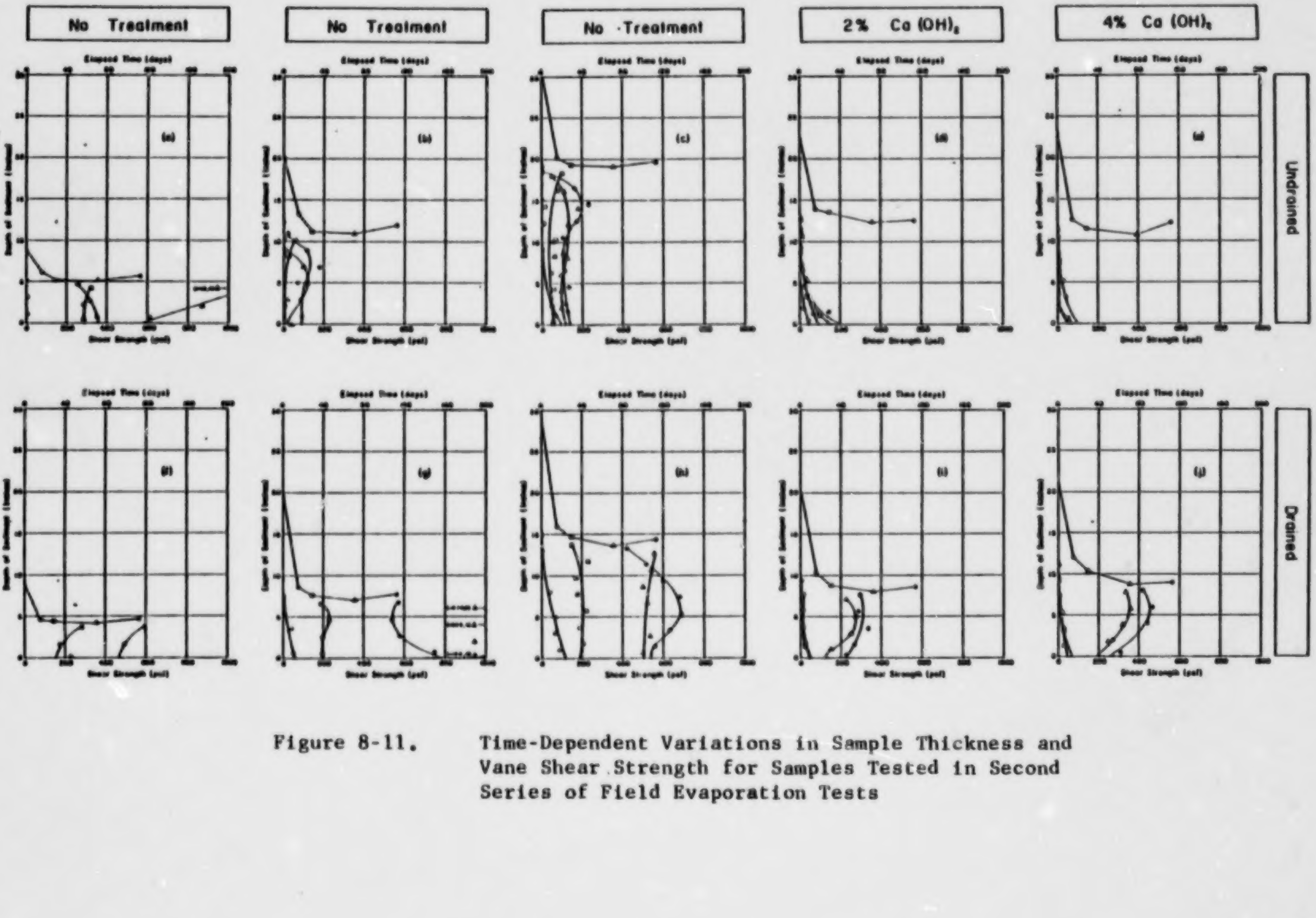


Figure 8-11. Time-Dependent Variations in Sample Thickness and Vane Shear Strength for Samples Tested in Second Series of Field Evaporation Tests

DISCUSSION

A comparison of the relative positions of the water retention curves in Figure 8-6 and the representative water retention curves presented by Yong and Warkentin (1966) shows that the curves for most of the dredged materials lie between those for clay and loam soils; this is consistent with the classification deduced from grain size analyses and Atterberg limits. The shape of the curves for the dredged materials also indicates organic materials with significant secondary consolidation. The two steeper portions (0.1 to 0.3 bars and 2 to 5 bars) of these curves are due to the loss of gravitational water and capillary moisture, respectively. Finally, the relative position of final water content (at 15 bars) of each curve correlates well with the clay contents of these materials (i.e. the higher the clay content, the higher the final water content). Higher extractive energies are required to remove the water from the finer capillaries of the materials with higher clay contents.

The objective of the three series of laboratory evaporation tests was to determine the major parameters which influence the rate of water loss and the strength-water content relationship for the undrained condition. There was no significant difference in the initial rate of water loss for lime-treated and untreated materials under the same test conditions. Figure 8-12 presents the laboratory results for untreated materials; the numbers beside each data point are the initial rate of water loss (in % per day), which was nearly constant for about 25 days, and the axes are the initial water content and thickness of the test samples. Although the data are erratic, it appears that the relative

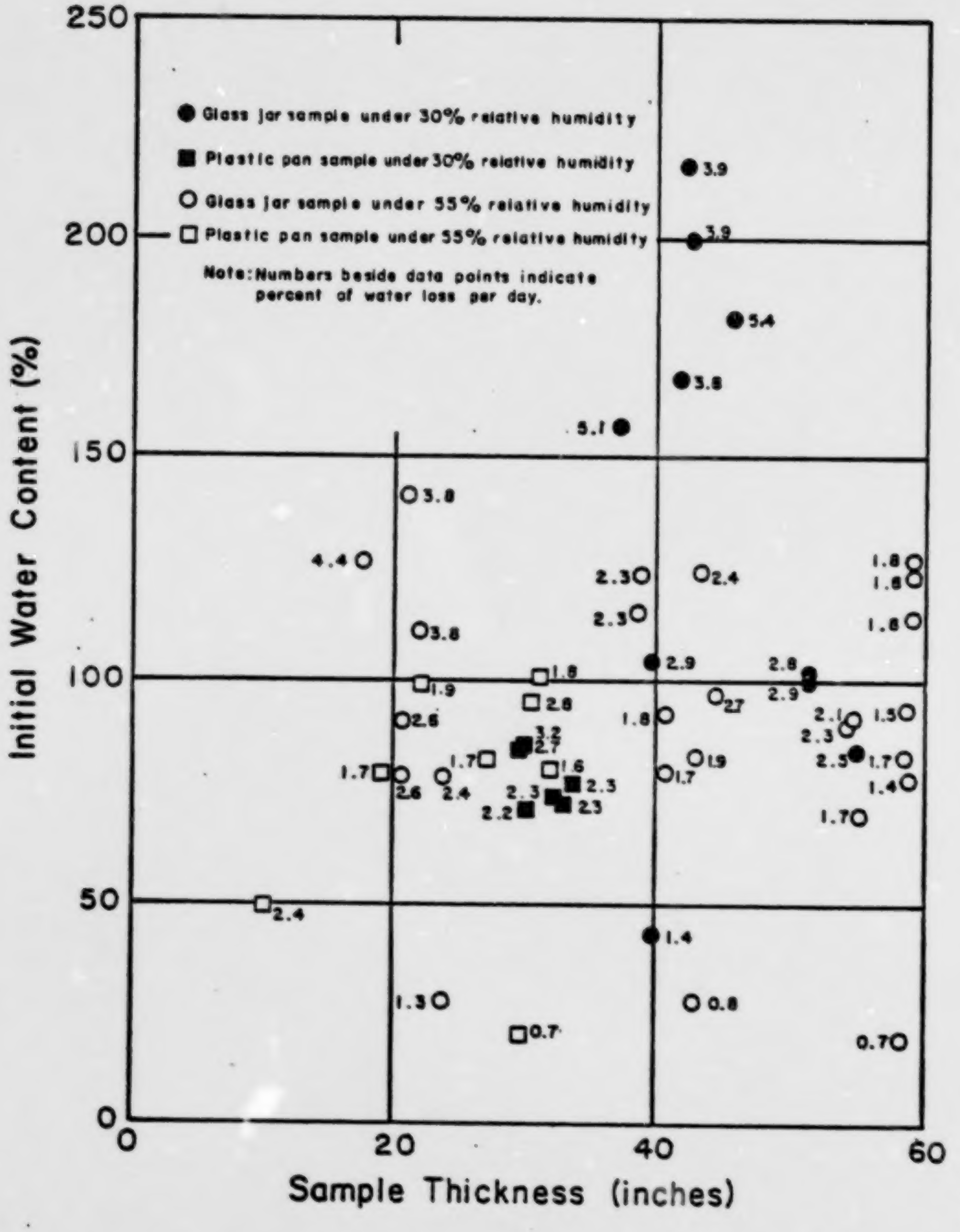


Figure 8-12. Effect of Initial Water Content, Initial Sample Thickness, Sample Surface Area, and Relative Humidity on Initial Rate of Water Loss in Laboratory Evaporation Tests

importance of the various parameters on water loss rates are in the order of (a) initial water content, (b) relative humidity, (c) sample surface area, and (d) sample thickness. As sample thicknesses were increased, the relative humidity seemed to be the primary factor controlling the initial rate of water loss.

Figure 8-13 presents the results of 90 vane shear strength tests on 41 untreated laboratory evaporation test samples at various water contents. Considering the variation in the dredged materials tested, the relationship between water content and shear strength is quite uniform for water contents less than about 60%; above water contents of 60%, however the results are much more erratic. The results for lime treated materials (not shown) were much more widely scattered, probably due in large part to the fact that shear strength is a function of curing time, as well as water content. As mentioned previously, the average total strength increase of lime treated materials was about twice that of untreated materials by the end of the laboratory tests. In the field evaporation tests the strength increase of drained materials was 4 to 10 times that of the undrained materials by the end of the tests; this is probably attributable in large measure to more complete consolidation.

For drained specimens lime treatment (at 2% and 4%) resulted in strengths that were 30% to 50% of those corresponding to the untreated specimens; this was apparently due to a lower rate of water loss and less consolidation. However, the strength of the lime treated material was less affected by rewetting caused by rain. Since the material used in the field tests was not one of those studied in the laboratory,

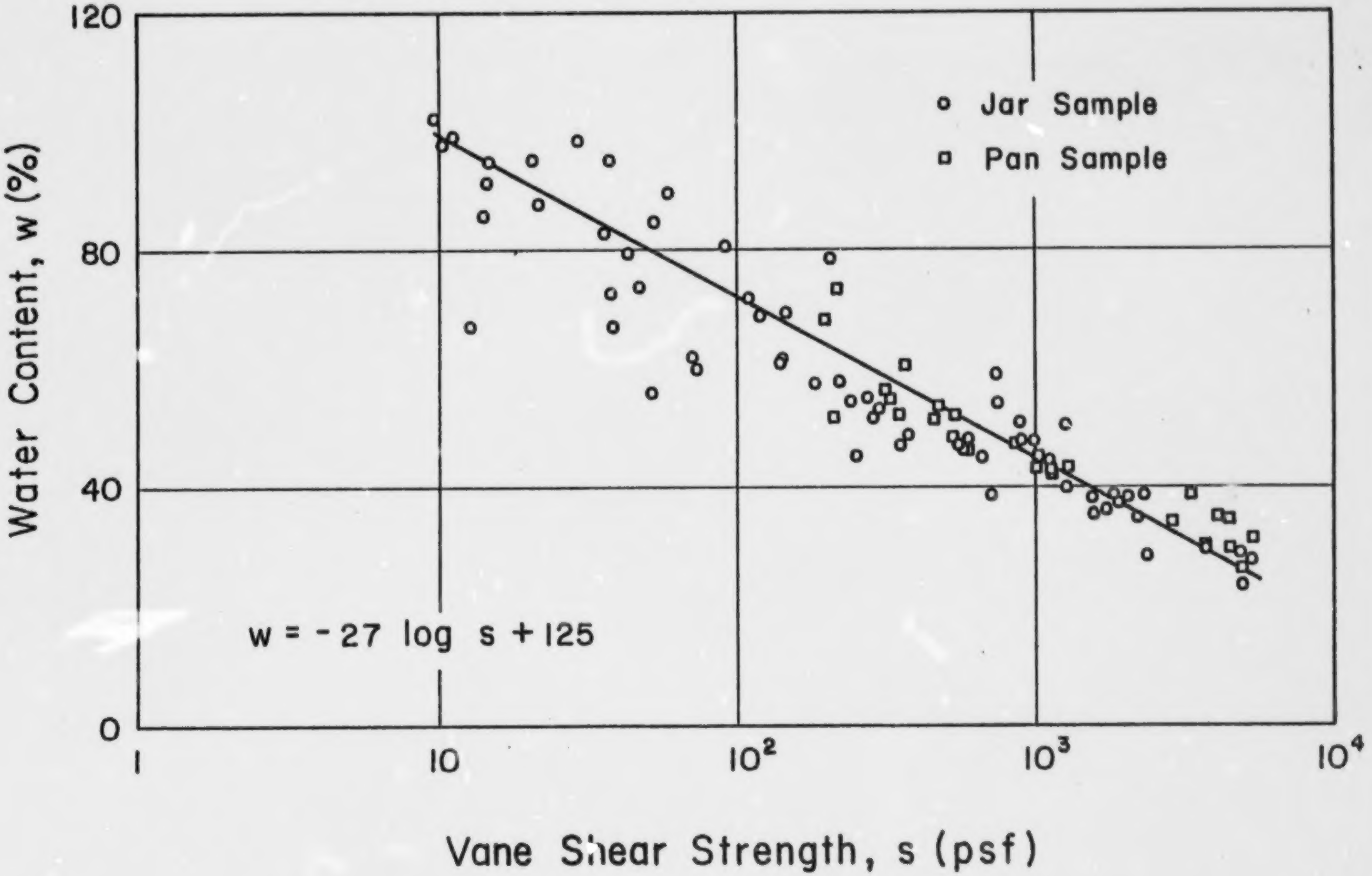


Figure 8-13. Correlation of Shear Strength with Water Content for Untreated Samples in Laboratory Evaporation Tests

no laboratory data on the effectiveness of lime treatment are directly available; perhaps the particular organics present in the material inhibit lime-soil reactions. Laboratory data on other dredged materials indicate that lime treatment is effective at higher soil densities. The field results show that strength increases in the material are due primarily to desiccation in the upper portions and consolidation in the lower portions of the sediments. A comparison of data from nine pairs of lime treated and untreated materials subjected to laboratory evaporation tests indicates that the lime treated samples were stabilized at a somewhat larger final volume than the untreated samples. Bonding due to soil-lime reactions during drying apparently stabilizes the material at a slightly larger void ratio. This cementation, as reflected by strength increases, may reduce volume changes due to secondary consolidation.

Materials with higher initial water contents and higher clay contents developed more and larger cracks on drying than other materials. In the laboratory evaporation tests, lime treated materials developed essentially no cracks within the small samples. However, in the field evaporation tests with larger samples, the lime treated material developed fewer, but larger and deeper, cracks than did the untreated material, indicating a higher cohesion in the lime treated soils or a greater degree of orientation of the clay particles. However, since flocculation tests show lime to be effective in flocculating the dredged materials, the cracking pattern is indicative of greater cohesion in the lime treated soils. Crack formation in the field may be the factor controlling the rate of water loss. The number of soil units is related to the frequency of the crack pattern; hence, after an array of cracks form, the number of continuous capillaries available for water to evaporate through the soil mass is reduced. The area across which evaporation takes place may be primarily the area of the cracks and wet spots in the disposal sites. Although the cracks may deepen during the drying process, the surface area for evaporation may still be less than the areas of the site and the rate of water loss would be correspondingly decreased. This may be offset by mixing the fine materials with the coarser materials to reduce the cohesion of the surface portion or by establishing vegetation to more uniformly distribute the water loss with depth.

CONCLUSIONS

The purpose of the laboratory and field evaporation tests described herein was to study the relative importance of various parameters on the rate of dewatering through evaporation. Laboratory tests and small scale field tests were used because actual field conditions are usually complicated by such factors as adverse hydraulic gradients (due to lower ground level and/or high groundwater table), reflooding, precipitation, moisture or heat convection due to wind, etc. Generally speaking, the relative importance of parameters that increase the water loss due to evaporation is in the order of (a) mixing, (b) initial water content, (c) relative humidity, (d) exposed surface area, (e) depth of sediment and (f) degree of lime treatment for similar types of dredged materials; however, this order may vary somewhat for different situations. Based on the results of this test program and the available data in the literature, the following conclusions may be advanced:

1. If conditions permit, the disposal site should be located on high land with a low groundwater table and good drainage conditions. In such a situation, most of the sediment dewatering will occur as drainage into the underlying soil. However, consideration must be given to possible groundwater pollution.

2. The mixing of dredged sediments in the containment areas can be very effective for dewatering the landfill if the process of mixing is properly scheduled. For example, for a two foot lift of spoil, the sediment may be allowed to dry until the rate of water loss begins to decrease and shear resistance develops; the top crust may then be mixed with the remaining material. Because the top crust has some strength, the mixing process may have a compactive effect, as well as one of increasing the rate of water loss.

3. Providing a coarse layer over the dredging landfill may minimize or prevent the formation of cracks, thus enhancing the rate of water loss from the lower layer.

4. Proper scheduling of the dredging and disposal cycle during seasons with low to average relative humidity would increase the rate of water loss and reduce the probability of reflooding and the development of adverse hydraulic gradients. Inland disposal sites may result in an increase in the rate of water loss due to the convection of moisture.

5. Lime treated organic dredged material may form a more open and stable soil structure. Because of this open and stable structure, it has larger capillaries and may retain more water in the voids; therefore, the final water content and initial strength may be lower. However, continued pozzolatic reactions may increase the strength with time, despite effects of rewetting, and the effect of secondary consolidation may be reduced. Hence, in the long-term view, the addition of lime may improve the engineering characteristics of the organic dredged material to a useful landfill.

6. Observations of the disposal sites in Toledo, Ohio, suggest that the surface vegetation on the dredging landfill may serve to stabilize the cracks and distribute the water loss more evenly through the upper layer.

CHAPTER 9

TRANSPIRATION

Flood plain deposits, shallow water areas, and wet soils are normally colonized by characteristic communities of vascular plants, and these deposits frequently densify and stabilize rather rapidly, even when the water table remains high and surface drainage is minimal. Correspondingly, deposits of polluted dredgings in a diked containment area are often high in water content and rich in nutrients, and part of the surface may be inundated. Based on observations at various diked disposal sites, vegetation apparently becomes established on the dredged spoil without assistance soon after a dredging season has ended. Although the specific types of vegetation depend on many factors, including the presence and/or availability of seed, condition of the spoil (especially the surface), time and duration of the dredging process, and depth of spoil deposit, the nature of the dredge spoil itself may present some special problems, since such materials are usually fine textured, high in organic content, and polluted with various toxic compounds. Hence, it is necessary to undertake a detailed study of the characteristics of plant communities usually found in wetlands.

While evaporation will remove large amounts of water from a free water surface, it is not quite as effective in dewatering partially saturated soil deposits, especially after an impedance layer has developed. On the other hand, plants draw water from beneath the soil surface and continue to transpire water vapor as long as appreciable amounts of water remain in the soil. Thus, a dense stand of plants may rapidly lower the water content of the surface layer (one to two feet) of soil to the wilting point (15 bars).

A number of physical changes occur as a soil layer desiccates; aeration increases, thereby permitting oxidation and related chemical changes, and the oxidation of reduced compounds make additional mineral nutrients available, thus stimulating vigorous plant growth. However, oxidation may also increase the solubility of toxic materials. Aeration generally permits increased root growth and more effective utilization of available moisture from deeper zones.

Plants, through normal and selective absorptive processes, assimilate large quantities of mineral nutrients, metallic ions, and other compounds; the extent and selectivity of these processes vary with the particular plants that are present. Plants also differ in their ability to assimilate and store carbohydrates. Many plant species with high transpiration rates are well adapted to growth on spoil areas, but have little direct economic value; however, other species combine these attributes with economic values. Therefore, manipulation of spoil deposition and the texture and moisture content of the substrate should be considered as means to encourage plant growth. Included in this chapter is a review and evaluation of information pertaining to plant growth, water consumption, and other related factors for plants found in alluvial deposits and other wetlands; then, this information is extended to study the anticipated behavior of areas composed of polluted dredge spoil (Stearns, Kobriger, Levenson, and Ringger, 1974).

CHARACTERISTICS OF PLANT COMMUNITIES IN WETLANDS

There are a variety of plant communities adapted to wetland (alluvial, poorly-drained, and submerged) sites normally found in nature. The duration and depth of inundation exerts a primary influence on community establishment, development, and survival. The inundation of dredge spoil sites appears to vary from site to site, from year to year, and from place to place within a site; hence, the subsequent descriptions of vegetation will proceed from communities adapted to prolonged submergence to those better adapted to dry surface conditions. These include emergent aquatic communities, annual weed communities, shrub communities, and sedge meadow communities. Table 9-1 lists the plants of these communities that are common in the midwestern United States. Conditions at any one diked disposal area may include both submerged and exposed substrate; in fact, diverse conditions may prove desirable for filtering pollutants and draining free water from the spoil.

Emergent Aquatic Communities

Areas where the land surface is inundated for long periods favor the development of plant communities capable of growth with the root zone continuously under water. These communities tolerate some change in water level and are dependent upon the nutrients in the mud; normally, they evaporate considerable amounts of water during the growing season. The emergent species are capable of high carbohydrate production and nutrient uptake; they store much of their production and nutrients in roots and rhizomes (Sculthorpe, 1967; Bernard and Bernard, 1973; McNaughton, 1966).

Emergent species include plants with water-borne and wind-borne seed. For seedling germination and establishment, most of these plants require an exposed, but wet, substrate. Only after the seedlings have become established can they survive inundation. Actual germination may be stimulated by submergence, such as for cattails (Bedish, 1967), but the seedlings must quickly grow to the surface. A few emergents, including wildrice and reed grass, germinate and become established under water. However, the use of vegetative structures as corms or rhizomes appears to be the most effective means for enhancing the rapid vegetation of continuously inundated areas.

T-9-1

Table 9-1

Wetland Plants Common in Midwestern United States

Emergent Aquatics and Semi-aquatics

English Name	Latin Name
Bullrush	Scirpus validus
Bullrush	Scirpus lacustris
Bullrush	Scirpus acutes
Bullrush	Scirpus cyperinus
Tule	Scirpus spp.
Rush	Juncus balticus
Rush	Scirpus fluvitalis
Soft rush	Juncus effusus
Sharp fruited rash	Juncus acuminatus
Cattail	Typha latifola
Narrow leaf cattail	Typha angustitolia
Reed	Phragmites
Reed grass	Phragmites communis
Burreed	Sparganium sep.
Sedge	Carex Lacustris
Fox sedge	Carex vulpinoidea
Spiker rush	Eleocharis acicularis
Wildrice	Zizania aquatica
Pipe wort	Eriocaulon septangulare
Butter cup	Ranunculus
Mare's tail	Hippuris
Arrowhead	Sagittaria latifolia
Manna grass	Glyceria striata
Water cress	Nasturtium
Celery	Apium
Rose mallow	Hibiscus militaris
Sweet flag	Acorus calamus
	Littorella uniflora
	Lobelia datmanna
	Schoenoplectus

Sedge Meadows and Sedge Marshes

English Name	Latin Name
Sedge	Carex cyperus
Reed canary grass	Phalaris arundinacia
Marsh grass	Spartina pectinacea
Manna grass	Glyceria striata
Blue joint	Calamogrostis canadensis

Annual Weeds and Grasses

English Name	Latine Name
Giant ragweed	Ambrosia trifida
Knotweed	Polygonum spp.
Nettle	Urtica diocia
Dock	Rumex spp.
Pigweed	Amaranthus spp.
Goosefoot	Chenopodium spp.
Beggars tick	Bidens spp.
Witch grass	Panicum spp.
Bermuda grass	Cynodon dactylon
Rice cut grass	Leersia oryzoides

Vegetable Crops and Other Crops

English Name	Latin Name
Snap beans	Phaseolus vulgaris
Tomato	
Cabbage	
Sweet corn	
Squash	
Pea	
Corn	
Alfalfa	
Dwarf wheat	Triticum aestivum
Tobacco	
Safflower	Carthamus tictorius
Saltbush	Atriplex nummularia
Cotton	Gossypium hirsutum
Sweet gale	Myrica gale

Shrubs and Woody Plants

English Name	Latin Name
Willow	Salix interior
Cottonwood	Populus deltoides
Dogwood	
Red osier dogwood	Cornus stolonifera
Buttonbush	Cephalantus occidentalis
Alder	Alnus spp.
River birch	
Citrus	
Mulberry	
Pine	

The texture variability and instability of the substrate make it difficult for plants to colonize a newly formed spoil. Instability may be overcome in part by a branched system of vigorous rhizomes (horizontal underground stems) or fibrous adventitious roots that bind and stabilize the soil particles (Sculthorpe, 1967). Roots of submerged plants must be able to resist bending stresses and terrestrial compression stresses, both of which are inherent in unstable substrates. The best engineered root-rhizome system appears to be a honeycomb structure of lacunate parenchyma (Williams and Barber, 1961), because this sytem is the most functional compromise for meeting both the mechanical and physiological (bringing oxygen down from the shoot to the anaerobic root) requirements of an aquatic existence. Some species which approach this ideal are reed grass (with its stout, spongy, excessively creeping, laterally branching rhizomes) and bullrush and cattail (which have tough, woody, freely branching rhizomes); other species capable of colonizing unstable substrates include Littorella uniflora and Lobelia datmanna, both of which form extensive swards to stabilize rough, loose, inorganic, and peaty soils.

Aeration, water pressure, and soil type and composition affect shoot and root growth characteristics. Optimal growth implies high productivity (rapid and dense growth), early reproduction, disease resistance, maximum root elongation and soil penetration, and abundant root hair formation. These characteristics are reflected in the rate and quantity of water uptake and loss, the quantity and quality of mineral uptake, and the chemical composition (percent minerals, protein, fat, carbohydrate, cellulose, tannin, etc.) of the plant.

In Michigan, Veatch (1933) noted the texture, hardness, and pH of the substrates on which optimum growth occurred for four species of common water emergents: bullrush, wildrice, cattail, and pipe wort. Bullrush grows on "hard" bottoms (except hard bedrock) in alkaline and hard water. Wildrice thrives on bottoms which are soft, fluid, organic mud or peat, thin peaty mud over calcareous clay, and clayey, inorganic, calcareous mud; all substrates should have a hardness of 1.6 to 4.5 gm/ℓ and a pH of 8.0 to 8.6. Cattail commonly grows under a wide range of soil conditions, but produces the heaviest growth on the more clayey muds and on a thin covering of black alkaline mulch over clay or calcareous sand-silt. Pipe wort commonly grows on peat, peaty sand, or clean non-calcareous sand of soft and nearly neutral or slightly acid water.

Reed and cattail commonly grow in slow moving waters with abundantly silty or muddy bottoms, and vigorous vegetative rhizome growth may be 100 cm per year (Sculthorpe, 1967). Haslam (1970) notes that reed can grow in semi-flooded gravel pits and can become established on soils ranging from fine-textured mineral soils to nutrient-rich peats. Based on studies of cattail communities in Mississippi. Alabama, Georgia, and Florida, Boyd and Hess (1970) found that substrates ranged from sands to heavy clays and from inorganic to highly organic soils. Other semi-aquatic species, including buttercup, burreed, Mare's tail, and arrowhead, can grow on partially silted gravel and sand. Muds support species such as Manna grass, burreed, Schoenoplectus, cattail, reed grass, rush, sedge, and canary grass, whereas water cress and celery grow on hard water banks (Sculthorpe, 1967).

Anaerobic conditions in the substrate influence growth. Oxygen is essential to root respiration, nutrient absorption, root elongation, root hair development, aerenchyma formation, and adventitious root development. Lack of oxygen in the substrate results in modification of the gross anatomy of the root system. Successful emergent aquatic plants can survive, at least periodically, in an anaerobic environment because of specialized tissues and physiological adaptations. Dean (1933) tested the effect of the combination of soil type and aeration on root systems of several emergents (including rose mallow, cattail, sweet flag, and arrowhead) normally adapted to poorly aerated soils. All species developed bulkier roots (extensive vertical growth and branching) and larger tops under aerated conditions in contrast to the shallow horizontal root system which developed under anaerated conditions; growth and development were greatest in muck, second in clay, and least in sand, except for rose mallow (which had maximum growth in anaerated sand) and arrowhead (which attained maximum growth in anaerated and aerated sand). Reed will grow in most anaerobic situations (Haslam, 1970), and cattail will grow successfully in anaerobic substrates provided the shoots are exposed to air (Bedish, 1967); bullrush is another aquatic emergent whose rhizomes respire anaerobically (Sculthrope, 1967). As seen briefly, soil type, soil texture and composition, aeration, and other substrate conditions (inundation, climate, etc.)influence the growth of emergent aquatic species.

Annual Weed Communities

Annual weed communities develop most often on disturbed or cultivated silts and clays subjected to brief flooding but with ample subsurface moisture. After the deposition of dredge spoil inside a diked containment area is completed, either temporarily or permanently, some spoils may drain sufficiently for the surface layers to dry. At this time the surface conditions are suitable for the rapid development of annual weeds, and the presence of seed is the controlling factor. Seeds accumulate on seasonally inundated agricultural soils, and germination proceeds almost immediately. Similarly, seeds of several species are usually present in quantity on pond bottoms exposed after a drawdown. Although dredge spoil from shallow areas or near the shore may contain viable seed, little is known of seed availability in dredge sites, and the problems associated with procuring ample seed in optimum germination conditions for weed species should be examined.

Seed for most of the annual weeds are carried by water, animals, or windblown trash; except for the thistles and other composites, none are regularly disseminated by wind. Seeds of many weedy species may survive flooding for considerable periods and remain viable for several years. A seed crop produced on spoil would be available for growth in future years, provided that it was not deeply buried. Seed germination requirements vary, but the requiremnt in many species is only a moist or wet substrate. Dormancy in some species is broken by exposure to a cold climate, and for some species germination is increased by the presence of soluble nitrate.

Species composition will vary with soil texture, nutrient levels, seed availability, and climatic conditions. In the upper midwestern U.S. and Great Lakes region, the species anticipated (including pigweed, goosefoot, beggars ticks, witch grass, dock, and several knot weeds) are those common to disturbed marshes, drained pond bottoms, and wet portions of fields. These plants soon form a vigorous dense stand which may reach over four feet in height; they include both fibrous and tap rooted species (Kutschera, 1960) and, under favorable conditions, may draw water effectively from the upper one to two feet of spoil. The water use of the annual weed communities on saturated agricultural soils and exposed pond bottoms is not well documented quantitatively (Stearns, 1956; Dale, 1964; Kadlec, 1962; Klopatek, 1974), but rapid growth of the plants and effective occupation of wet disturbed areas indicates that they place strong demands on the mineral and water resources. Many of the annual weed species, particularly those adapted to growth on fine grained soils, are favored by high nutrient concentrations.

Carbohydrate fixation is efficient and stands of annual weeds may produce as much biomass as a corn crop (Klopatek, 1974). Since most of the biomass is in the above-ground portions of the annual weed communities, much of the organic matter produced could be removed readily by harvest before the next period of spoil deposition. The available evidence indicates that these plants are also relatively tolerant of organic pollutants (Stuckey and Wentz, 1969).

Therefore, when dredging operations can be completed early in the growing season with about two feet of spoil deposition, and where partially drained spoil surfaces permit germination, an annual weed community offers an attractive approach to dewatering, since these communities could be established rapidly and relatively economically during one growing season. Except for the allergenic problems associated with giant ragweed, most of these plants have no detrimental effects and provide considerable food and cover for common wildlife species.

Shrub Communities

Shrub communities are common to both sandy river bars and frequently inundated areas of organic soils. The willow and cottonwood communities develop rapidly in river alluvium, exposed lake beds, and similar wet sites; the small windblown seeds frequently germinate within 24 hours after reaching a moist surface, and very wet exposed mineral soils are ideal substrates. The seed of these genera cannot be stored readily and must be collected during the season of use. Seedlings of both willow and cottonwood are susceptible to surface drying during the first few weeks, and seed beds must remain moist for 30 to 60 days. Cottonwood seedlings are quite susceptible to fungus attack, but willow seedlings appear to be more resistant; however, fungi could become a problem in soils that are high in organic matter and have a neutral or higher pH. High temerpatures during early seedling development may also result in considerable mortality. Nevertheless, willow and cottonwood can be effectively and easily propagated by cuttings, which give excellent survival and rapid growth.

Both willow and cottonwood will grow on a wide range (from sand to clay) of soil textures; however, optimum soils for cottonwood are moist, but well drained, fine sandy loams or silts with the water table near the surface. Willows have extensive, but shallow, root systems; when supplied with adequate moisture and nutrients, the seedlings can reach a height of four feet in the first year. Under favorable conditions, stands of willow or cottonwood may reach heights of 20 to 30 feet in five years. Shrub communities could probably be harvested on about a three to six year rotation. Much of the nutrient uptake is released each year during leaf-fall and subsequent decomposition. Shrub communities are adapted to reflooding and additional deposition, provided the depth of the material deposited is regulated to permit recovery.

Willow and cottonwood both sprout readily, and harvest of the aboveground material will usually be found by the rapid regrowth of shoots. Both groups show promise for intensive cellulose production. Other wetland shrubs are relatively slower to develop, but their presence may be desirable to provide aesthetic qualities or the diversity essential to good wildlife habitat. Such shrubs include red osier dogwood, buttonbush, and alder. Although alders are common wetland shrubs found in peat soils, the establishment of dogwood and other shrubs from seed requires cold weather and time. However, most wetland shrubs can be established vegetatively, and they spread rapidly.

Sedge Meadow Communities

Sedge meadow communities normally develop in poorly drained areas where inundation is seasonal and of relatively short duration. Plants often grow in clumps or clones and do not tolerate extended flooding; therefore, for short time spans (on the order of one to five years) such communities do not appear to offer any major help in stabilizing deposits of dredge spoil. However, some of the component species may assist in providng diversity for wildlife, especially when mixed with shrubs; among these species are several grasses, such as blue joint, Manna grass, reed canary grass, and marsh grass. Separately or in mixture, these grasses are adapted to wet conditions, and their establishment from seed appears feasible. Reed canary grass has demonstrated high production rates on fertile saturated soils; it withstands partial submergence, especially during the dormant season, and it is a useful rough-forage grass. Sedge meadow communities appear to be best adapted to the later stages of a landfill operation when no further deposition is anticipated for several years.

WATER CONSUMPTION BY PLANTS

In general, the literature on the requirements and use of water by plants concentrates on crop plants and forest trees, although some attention is given to the annual weed competitors of crops. Water relationship in arid regions have also been the subject of considerable attention, but the use of water by emergent aquatic species has received relatively little attention. Much of the literature in the last decade has been concerned with the methodology for obtaining estimates of evapotranspiration from agricultural crops on well drained soils, especially in areas where irrigation is necessary. Definitive data on water use by annual weeds and emergent aquatics is not abundant, but published data may permit some general conclusions and reasonable extrapolations.

A few plant species have been shown to have the ability to remove water in excess of that evaporated from a free water surface (Palmer, Trickett, and Linacre, 1964). More important in the dewatering of dredge spoil is the fact that plants remove water at a rapid rate long after the soil surface has dried. Water removal by plants occurs when the subsoil is saturated, and it may continue until the wilting point is reached (that is, a capillary water tension of approximately 15 bars). The associated amount of water is called the available water for plants.

The potential evapotranspiration rate, E_p, is the maximum water loss anticipated from plant cover when water supply is unlimited (Thornthwaite and Mather, 1957). As the soil-water tension increases, actual evapotranspiration is reduced, and the degree of reduction depends upon the species present. Plant characteristics, such as root depth and distribution, height, leaf structure, and growth pattern, influence the actual amount of water transpired. In the temperature climates of North America potential evapotranspiration is often zero in several of the winter months. In July E_p reaches only 0.098 inches per day at Eureka, California, in contrast to 0.276 inches per day at Las Vegas, Nevada (see Table 9-2). The highest potential evapotranspiration rates occur in hot, arid areas, and the lowest rates in cloudy, humid, coastal regions.

Plants responsible for water depletion are called phreatophytes (well plants); such plants have roots that grow down to the water table and effectively tap the available moisture at this level. Work on phreatophytes provides much evidence regarding the dewatering ability of plants (Horton, 1973). In general, the deeper rooted trees and shrubs of river bottoms appear to be more effective in removing water than do the forages and grasses, which may form relatively thin stands). As pointed out by El Nadi and

Table 9-2

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Mean Potential Evapotranspiration (After Stearns, 1961)

	Mean Potential Evapotranspiration (inches per day)													
Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Lat Deg	"I" Value
Arizona														
Flagstaff	0	0	0.010	0.044	0.081	0.121	0.143	0.136	0.094	0.057	0.017	0	35.1	30.02
Tucson	0.017	0.028	0.050	0.086	0.150	0.224	0.246	0.222	0.185	0.104	0.044	0.025	32.1	101.00
Arkansas														
Ft. Smith	0.008	0.018	0.040	0.087	0.139	0.206	0.226	0.215	0.156	0.086	0.026	0.008	35.4	82.33
Texarkana	0.017	0.018	0.040	0.097	0.151	0.216	0.236	0.224	0.165	0.086	0.035	0.017	33.5	91.59
California														
Bakersfield	0.017	0.027	0.050	0.087	0.128	0.194	0.235	0.215	0.156	0.095	0.043	0.016	35.3	90.36
Eureka	0.040	0.053	0.059	0.066	0.084	0.100	0.098	0.104	0.083	0.065	0.050	0.047	40.8	41.53
Sacramento	0.016	0.036	0.050	0.077	0.106	0.160	0.183	0.171	0.135	0.085	0.042	0.016	38.5	73.85
San Diego	0.052	0.055	0.069	0.086	0.104	0.118	0.140	0.144	0.113	0.095	0.070	0.050	32.6	71.16
Colorado														
Denver	0	0	0.020	0.055	0.096	0.150	0.184	0.161	0.104	0.056	0.017	0	39.7	44.44
Grand Junction	0	0	0.020	0.066	0.108	0.162	0.209	0.184	0.125	0.056	0.008	0	39.0	55.11
Pueblo	0	0	0.020	0.055	0.106	0.155	0.195	0.171	0.114	0.056	0.017	0	38.2	49.66
Idaho														
Boise	0	0	0.020	0.067	0.098	0.142	0.202	0.176	0.105	0.055	0.016	0	43.6	47.20
Kansas														
Wichita	0	0	0.020	0.066	0.118	0.184	0.232	0.205	0.135	0.066	0.017	0	37.7	67.23
Minnesota														
International Falls	0	0	0	0.023	0.088	0.146	0.170	0.143	0.094	0.036	0	0	48.6	27.82
Montana														
Billings	0	0	0	0.045	0.100	0.144	0.192	0.165	0.105	0.055	0.008	0	45.7	41.09
Butte	0	0	0	0.034	0.075	0.118	0.154	0.130	0.074	0.037	0	0	46.0	22.46
Glasgow	0	0	0	0.046	0.101	0.146	0.196	0.155	0.094	0.036	0	0	48.2	37.29
Nebraska														
Grand Island	0	0	0.010	0.066	0.108	0.175	0.209	0.184	0.125	0.056	0.008	0	40.9	52.29
Scottsbluff	0	0	0.010	0.045	0.098	0.155	0.189	0.176	0.105	0.055	0.008	0	41.9	44.03
Nevada														
Ely	0	0	0.010	0.044	0.084	0.125	0.160	0.150	0.094	0.047	0.008	0	39.1	33.61
Las Vegas	0.008	0.018	0.040	0.098	0.164	0.244	0.276	0.249	0.187	0.085	0.026	0.016	36.1	100.76
New Mexico														
Albuquerque	0	0.009	0.030	0.065	0.116	0.182	0.202	0.181	0.135	0.066	0.017	0	35.0	64.24
Roswell	0.008	0.018	0.040	0.076	0.125	0.192	0.202	0.190	0.135	0.076	0.026	0.008	33.4	73.14
North Dakota														
Bismarck	0	0	0	0.045	0.100	0.157	0.192	0.165	0.094	0.046	0	0	46.7	34.08
Devils Lake	0	0	0	0.034	0.088	0.146	0.183	0.155	0.094	0.036	0	0	48.0	33.12
Fargo	0	0	0	0.034	0.075	0.157	0.192	0.153	0.094	0.046	0	0	46.8	37.42
Oklahoma														
Oklahoma City	0	0.009	0.030	0.076	0.129	0.207	0.228	0.215	0.156	0.075	0.026	0.008	35.5	77.00
Oregon														
Burns	0	0	0.020	0.056	0.086	0.116	0.176	0.152	0.094	0.046	0.008	0	43.6	36.66
Portland	0.008	0.017	0.040	0.067	0.100	0.131	0.154	0.142	0.105	0.064	0.032	0.014	45.5	47.15
Roseburg	0.015	0.025	0.040	0.067	0.098	0.129	0.151	0.140	0.105	0.064	0.032	0.015	43.2	46.35
South Dakota														
Huron	0	0	0	0.045	0.111	0.168	0.202	0.176	0.116	0.055	0	0	44.4	45.26
Rapid City	0	0	0	0.045	0.086	0.142	0.189	0.164	0.105	0.064	0.008	0	44.0	39.85
Texas														
Amarillo	0	0	0.030	0.065	0.115	0.169	0.202	0.181	0.125	0.066	0.026	0.008	35.2	63.20
Brownsville	0.036	0.056	0.080	0.127	0.189	0.228	0.226	0.218	0.196	0.136	0.073	0.044	25.9	123.77
Dallas	0.009	0.018	0.050	0.097	0.150	0.224	0.257	0.244	0.175	0.101	0.035	0.017	32.7	97.59
San Antonio	0.017	0.028	0.060	0.107	0.171	0.222	0.232	0.222	0.175	0.106	0.044	0.026	29.6	105.60
Utah														
Salt Lake City	0	0	0.020	0.055	0.108	0.150	0.197	0.172	0.114	0.056	0.017	0	40.7	49.98
Washington														
Olympia	0.015	0.017	0.040	0.067	0.088	0.118	0.141	0.130	0.094	0.064	0.032	0.014	46.9	37.57
Spokane	0	0	0.020	0.057	0.101	0.146	0.183	0.155	0.094	0.046	0.008	0	47.6	47.60
Wyoming														
Casper	0	0	0	0.044	0.085	0.140	0.175	0.162	0.094	0.046	0	0	42.7	35.99
Sheridan	0	0	0	0.045	0.086	0.142	0.176	0.152	0.094	0.046	0	0	44.7	35.53

Calculated from U. S. Weather Bureau mean monthly temperatures using tables by Thornthwaite and Mather (1957).

Hudson (1965), plant height has an appreciable effect on water loss; their study also indicated that, in the presence of ample moisture, soil texture has little effect on water loss from either wheat or alfalfa. In arid areas removal of water by vegetation may range from a few inches to 7 acre feet per year (Robinson, 1958), and values of 4.0 to 4.5 acre feet per growing season are commonly found. In one California study (Young, 1933) the consumptive use of water was found to be very high; salt grass and Bermuda grass showed consumption rates of almost 43 acre inches per year, and willows manifested 53 acre inches. For emergent aquatic species, the rush exceeded the willow, while tule and cattail indicated even greater consumptive use. Similar rates were found in other studies (Taylor and Nickle, 1933), and tule water loss under most natural conditions was observed to exceed open pan evaporation. A recent study in Arizona (McDonald and Hughes, 1968) indicated very rapid water removal by cattail (approximately 100 acre inches per year) as compared to Bermuda grass (73 acre inches per year); the latter was measured with the water table at 3.5 feet below the surface. As a general rule, the water loss is greatest when the water table is shallow (Fletcher and Elmendorf, 1955).

Throughout these and other studies the investigators note that the water loss is strongly influenced by the oasis effect (that is, surrounding areas with warm dry surfaces may increase the water loss from experimental plots). It is probable that some inland dredging containment areas may be subjected to an oasis effect, particularly when these areas adjoin parking lots or industrial developments. The results from some representative studies on water consumption by plants are presented in the following sections; grouping is on the basis of economically comparable groups and groups of similar life form.

Grasses

McIlry and Angus (1964) examined the relationship among grass, water, and soil evaporation at Aspendale, Australia, and they state that:

> Evaporation from well-water and grass (potential evaporation) consistently exceeded that from free water and exceeded more than that from wet soil. The latent heat of potential evaporation also consistently exceeded the net energy available.

The additonal energy input may be attributed to the "oasis effect", which utilizes advective heat. The potential evapotranspiration rate of grass was correlated with the water loss associated with several other situations, and the overall ratios for the different conditions are listed in Table 9-3.

Table 9-3. Comparison of Potential Evapotranspiration Rate of Grass with Evaporation Rates for Different Conditions

Condition	Ratio
Grass to soil	1.40
Grass to wet soil	1.20
Grass to Australian standard evaporation tank	1.05
Grass to Class A evaporation pan	0.84

Ekern (1966) examined the evapotranspiration rate of Bermuda grass sod planted in Wahiawa, Hawaii. At high values of E_P, the consumptive use of water by the sod was essentially the same as that measured by a Class A evaporation pan. As the soil-water tension increased, the grass maintained a high rate of water use until a value of one bar was exceeded, beyond which point it was no longer able to maintain these rates as the soil-water tension increased. The actual evapotranspiration rate, E_T, was directly related to the soil-water tension by the values given in Table 9-4.

Table 9-4. Relationship between Soil-Water Tension and Evapotranspiration Ratio

Soil-Water Tension (bars)	E_T/E_P
0 to 0.23	1.10 to 0.95
0.50	0.81
0.70	0.33

Tovey, Spencer, and Muckel (1969) compared the evapotranspiration rates of Tifway and Tifgreen bermuda grasses in Reno, Nevada to determine appropriate watering regimes for a blue-grass-fescue mix and for bermuda grass hybrids on loam and sandy loam soils. In the blue grass-fescue sod most roots were in the top 6 to 8 inches, and root development was most extensive when adequate moisture was present. Deeper rooting of the bermuda grasses allowed them to utilize moisture more effectively than did the shallow-rooted lawn grasses. Water use by the bermuda grass hybrids ranged from 0.13 inches per day in the cooler part of the season to 0.23 inches per day when temperatures were the highest. Neither grass type was able to transpire more water than the free water evapoartion rate. Tifway and Tifgreen hybrid bermuda grasses are very temperature sensitive, and they brown quickly with frost; growth is best when the temperature is above 50°F.

Hibert (1969) investigated the change in the water yield obtained by converting a forested catchment to grass, and he reported:

> A 22-acre catchment in the southern Appalachicna was cleared of hardwood forest...and seeded to Kentucky 31 fescue grass... Water use by the grass cover was closely related to the amount of grass produced. During years when grass production was high, water yield from the catchment was about the same as or less than the expected yield from the original forest. As grass productivity declined, water yield gradually increased until it exceeded the predicted yield from the forest by over 5 inches annually. The grass appeared co evaporate more water early in the spring and less water late in the summer than the original forest cover.

Woody Plants

Citrus trees transpire less water per unit land area than most common agricultural crops (Jensen and Haise, 1963). At Lake Elsinore the ratio of E_T to E_{lake} ranged from a high of 0.88 in February to a low of 0.40 in May with a mean of 0.51 for a 12-month period. Canopy resistance to evaporation in a citrus orchard may be the major factor which depresses E_T so far below E_P. However, E_T from citrus groves in a hot, arid climate may be affected by the wind speed, and the aging of leaves influences the water use of an orchard by increasing canopy resistance.

Naoi and Sekiguchi (1970) examined the water economy of mulberry under different soil moisture conditions, including irrigated plots, half-irrigated plots, and non-irrigated plots. The evapotranspiration rate, E_T, during the growing season (July through September) was 0.24 inches per day in the irrigated plot, 0.13 inches per day in the half-irrigated plot, and 0.05 inches per day in the non-irrigated plot. They suggest that the optimum soil moisture in a mulberry field is from 50% to 100% of the available water, indicating that mulberry is a candidate for saturated dredge spoils (100% available water). Under optimum soil moisture conditions the average E_T of a mulberry field is about 0.23 inches per day in the summer season. In later studies on mulberry Naoi (1970) reported that the daytime average transpiration from the plant and evaporation from the soil for six days were 0.16 inches per day and 0.05 inches per day, respectively; hence, the evaporatranspiration rate, E_T, was 0.21 inches per day. He further stated

> Evidently 50% to 65% of the solar radiation consumed for evapotranspiration was latent heat. Evaporation ability (of the soil surface) in the plant canopy differed by height from the ground and the evaporation (from the soil surface) increased with height.

Water consumption, E_T, in the mulberry field was almost the same as measured from pan evaporation. The leaves at the highest position in the plant canopy transpired most effectively

Sinclair (1960) reported that the evapotranspiration rate in southern California during the dry season

> Exhausted all available moisture in the six feet of soil under the shrubs and pine... . 15 inches of rainfall or more than half, (i.e., of the total) were lost annually by evapotranspiration.

Other studies have involved the manipulation of forest cover to achieve increased water yield and a measure of the water use by trees. For example, in western North Carolina the clear cutting of a forested watershed increased the yield from 40 to 56 inches, thereby indicating the possible use by trees of about 16 inches per season (Hewlett, 1966).

Cotton

Palmer, Trickett, and Linacre (1964) studied the evapotranspiration of saltbush and cotton relative to soil-moisture stress in the Australian semi-arid zone. Plants were grown in a sandy clay loam soil at a high density; by restricting the height to about 7 inches, each species formed a low, uniform mat of vegetation. Under the climatic conditions and the experimental design used, cotton is capable of removing more water from the soil (evapotranspiration was 0.36 inches per day in the summer and 0.11 inches per day in winter) than would be expected with free-water surface evaporation. Stern (1967) also examined the seasonal water loss of irrigated cotton in Australia, and he reported

> Averaged over the year, evapotranspiration directly after irrigation (E_{TI}) was greater than the Penman estimate of potential evaporation (E_P) but less than the evaporation from the standard Australian tank (E_{tank}). The mean annual ratios were 1.2 (E_{TI}/E_P) and 0.9 (E_{TI}/E_{tank}). The rate of E_T was a function of soil moisture, declining rapidly as the available moisture fell below 60%.

He concluded that the advection of energy persisted in an arid environment for most of the year, particularly during periods of rapid height increases when ground cover was incomplete, and the surface roughness caused by crops enchanced E_T. Meterlerkamp and Cackett (1970) studied the effect of moisture stress on evapotranspiration and the growth of cotton in Rhodesia and found that the E_T/E_P ratio and the growth decrease rapidly when 70% of the available water has been removed from the top four feet of soil.

Vegetable Crops

Evapotranspiration rates at Geneva, New York were compiled for irrigated crops by Peck, Vittum, and Gibbs (1968), and the results are summarized in Table 9-5; available soil water was maintained above 50% capacity in the top two feet for the vegetable crops. Denmead and Shaw (1959) studied the evapotranspiration rate for corn in relation to its stage of development. The ratio, E_T/E_P, was calculated at eleven sites throughout Iowa over five growing seasons, and it was found that, prior to silking, E_T/E_P increased in a sigmoid manner from 0.36 at the planting date to 0.81 at silking, after which point it remained constant at 0.81 for 16 days and then declined. Presumably, the changing ratio resulted from increasing leaf area index until flowering, followed by declining physiological activity soon after commencement of ear growth.

Other Crops

Rosenburg (1969) examined the seasonal patterns of E_T by studying irrigated alfalfa at Mead, Nebraska. The maximum value for E_T during early spring was approximately 0.26 inches per day, but strong local and regional advection in late spring increased E_T to values as high as 0.47 inches per day, while during the hot humid summer the maximum value for E_T was 0.30 inches per day.

Sugimoto (1970) examined seasonal variations of E_T for Indian rice plants in Japan. The daily mean value of E_T was 0.25 inches per day in the dry period and 0.23 inches per day in the wet period.

Table 9-5

Summary of Evapotranspiration Rates of Vegetable Crops at Geneva, New York
(After Peck, Vittum, and Gibbs, 1968)

Vegetable Crops	Season	Minimum Daily Evapotranspiration (inches per day)		Yearly Mean (inches)		
		E_T	Date	E_T	E_P	E_T/E_P
Alfalfa	June 1 to Sept. 30	0.15	7/26	1.58	2.36	0.67
Tomatoes	July 1 to Sept. 30	0.17	7/29	1.30	1.69	0.77
Snap beans	July 11 to Aug. 20	0.17	8/4	0.63	0.83	0.76
Cabbage	Aug. 1 to Sept. 30	0.17	8/16	0.91	1.02	0.88
Sweet corn	July 11 to Sept. 10	0.18	7/31	0.91	1.26	0.72
Squash	July 1 to Sept. 30	0.16	7/31	1.18	1.65	0.72
Peas	June 1 to June 30	0.21	6/30	0.55	0.63	0.88

The consumptive use of water by drarf wheat was examined by Srivastava (1972) in India. In an irrigation-and-manurial trail on mixed black soil, the mean total consumptive use for the season varied from 15.6 inches to 20.4 inches, corresponding to 30% and 60% of the available soil moisture.

Chouteau, Loche, Renier, and Tancogne (1968) found the actual E_T of watered tobacco cultures to reach a maximum about the sixtieth day of vegetation growth; this maximum value was not very different from the E_P value of 0.18 inches per day. Near the wilting point, E_T approaches the flow rate due to capillarity potential (0.04 to 0.06 inches per day).

The evapotranspiration rate of safflower at three densities of sowing was examined by Stern (1965) in Australia, and he reported that

> E_T was related to potential free-water evaporation, E_F, as calculated by the Penman formula (Penman, 1956). Except at the rosette stage and during the transition period leading to elongation, there was no measurable difference in E_T between densities. The ratio of E_T/E_F was 1.57 during elongation and 1.25 between elongation and flowering falling to less than 1.0... before any marked depletion of soil water in the root zone. Average E_T over the cropping period was 3.1 mm per day (0.12 inches per day)... . The high ratios of E_T to potential evaporation were due to bulk advective conditions... .

Thornthwaite and Mather (1955) documented the maximum value of E_T for grass, oakwood, pine forest, and moist sand at Riverside, California and Miami, Florida for days in June, when total solar and sky radiation are at a maximum, and their results are summarized in Table 9-6.

Table 9-6. Maximum Daily Evapotranspiration

	Evapotranspiration Rate (inches per day)			
Location	Grass	Oakwood	Pine Forest	Moist Sand
Riverside, California	0.19	0.22	0.23	0.25
Miami, Florida	0.18	0.20	0.21	0.22

MINERAL RELATIONS AND EFFECTS OF POLLUTANTS

In order to grow successfully, a plant must be able to accommodate to the chemical milieu in which it takes root. Although knowledge of the effects of pollution on aquatic and wetland plants is relatively limited, enough data has been published to suggest which groups may accommodate to the chemical regime of polluted dredge spoil.

The mineral requirements and tolerances of the annual weed communities are probably very comparable to those of crop plants. The annual weed communities may develop in relatively infertile situations, but they make good use of mineral levels that are considerably higher than those normally found in fertilized fields of crop plants. The emergent aquatic communities also appear to compete successfully in wetlands with low fertility. The exchanges of nutrients between water, bottom muds, and plants also help to regulate the levels and perhaps lessen the damage from excessive nutrient concentrations. The shrub communities and grasses (such as reed canary grass) also appear adaptable to a wide range of nutrients. In any case all plants require nitrogen, phosphorous, and potassium in appreciable amounts and lesser amount of calcium, iron, sulphur, magnesium, etc. However, availability is the question; although essential minerals may be present in quantity, they may be in insoluble compounds and therefore unavailable to plants.

Water areas, including marshes, ponds, and shallow lakes, created by strip-mining in Ohio are often characterized by a low pH (resulting from H_2SO_4 production under oxidative conditions), the presence of overburden materials (primarily FeS_2, $FeCO_3$, and $CaCO_3$), and a leached soil zone several feet thick lacking available phosphorous and potash (Riley, 1960). Emergent aquatics common to these shallow lakes are narrow leaf cattail, common cattail, arrowhead, fox sedge, sharp fruited rush, soft rush, burreed, and bullrush. Narrow leaf and common cattail were by far the most abundant vascular plants growing in these harsh and unstable environments. Arrowhead relies more on the aqueous substratum than the soil for its nutrients, especially under conditions of poor soil aeration (Dean, 1933).

Stuckey and Wentz (1969) recorded the viability of aquatic and semiaquatic plants on the banks and in the shallows of polluted and unpolluted rivers in Ohio (Table 9-7). Although certain species tolerate pollution, it is much more difficult to find plants that not only grow in polluted conditions but also detoxify the pollutants. Seidel and Kickuth (1967) discovered that members of the bullrush (Scripus lacustris) family can absorb toxic materials which do not normally occur in the higher plants but which are frequently found in domestic and industrial wastes. Bullrush can absorb phenol, salicylic acid, and other aromatic compounds in considerable quantities and metabolize them into carbon dioxide and water. By metabolic oxidation and scission of the aromatic ring, bullrush can adapt to tolerate concentrations of 900 mg phenol per liter of water without damage. The degradation output is about 8 mg phenol per 100 gm of fresh weight in 24 hours. Other Scirpus species may grow in a wide range of conditions. For example, Scirpus Acutus occupies soils which are simply wet as well as those under as much as six feet of water; and it tolerates water with high calcium levels, marly soil, moderately salty or alkaline water, pH levels from 6 to 9,and sulphate concentrations as high as 1300 ppm. Scirpus validus colonizes shallow water (up to 2.5 feet deep) and thrives in unstable habitats, such as streambanks, roadside ditches, and places that are dry in some seasons and flooded in others (Smith, 1973).

The ability of plants to adapt to concentrations of heavy metals has long been a subject for investigation. Some information has been gained

Table 9-7

Pollution Tolerances (After Stuckey and Wentz, 1969)

Species Sensitive to Pollution

- Justica americana (Water willow)
- Saururus cernuus (Lizard's tail)
- Phystostegia virginiana (Flase dragonhead)
- Rumex verticillatus (Water dock)
- Samolus parviflorus (Water pimernel)
- Lippia lanceolata (Frog fruit)
- Helenium autumnale (Sneezeweed)
- Amaranthus tuberculatus (Water hemp)

Species Tolerant of Pollution

- Polygonum hydropiper (Water pepper)
- Polygonum persicaria (Lady's thunb)
- Polygonum pennsylvanicum (Pinkweed)
- Sagittaria latifolia (Arrowhead)
- Polygonum coccineum (Smartweed)
- Polygonum lapathifolium (Smartweed)
- Polygonum punctatum (Water smartweed)

Species Thriving at an Effluent Outlet from a Large Industrial Complex - Highly Tolerant of Chemical Pollutants

- Alisima plantago - aquatica
- Ambrosia trifida
- Cyperus erythrorhizos
- Cyperus esculentus
- Cyperus ferruginescens
- Echinochloa pungens
- Eleocharis erythropoda
- Scirpus validus
- Polygomum hydropiper
- Polygomum persicaria
- Polygomum pennsylvanicum
- Sagittaria latifolia
- Polygomum lapathifolium
- Potamogeton foliosus

Species Tolerant of or Indifferent to Pollution

- Echinocholoa pungens (Wild millet)
- Leersia oryzoides (Rice cut-grass)
- Ambrosia trifida (Giant ragweed)
- Utrica dioica (Stinging nettle)
- Arctium minus (Common burdock)
- Bidens frondosus (Beggar's tick)
- Lycopus americanus (Water horehound)
- Mimulus ringens (Monkey flower)
- Alisima plantago-auqatica (Water plantain)
- Cyperus esculentus (Yellow nut-grass)
- Eleocharis erythropoda (Creeping spike-rush)
- Impatiens capensis (Spotted touch-me-not)
- Rorippa islandica (Yellow cress)
- Rorippa sylvestris (Creeping yellow cress)
- Rumex altissima (Pale dock)

from attemps to establish plants on mine wastes, but these studies have demonstrated that there are considerable differences in tolerance to metals and some differences in the way in which metal concentrations are reflected in the plants. For example, low levels of copper in soils are reflected in the amounts found in the plant, but the uptake at higher levels is not linearly related to metal content, and at concentrations above 2000 ppm most plants cannot grow (Nicholls, Provan, Cole, and Tooms, 1965). In contrast, a moderately good linear correlation between plant and metal concentrations is found for zinc, cobalt, chromium, and nickel (Lyon, Brooks, Peterson, and Butler, 1968). Some plants readily accumulate metals in excess of the concentrations in the soil, and in many plants the concentrations in the roots greatly exceed those found in the tops. The examination of a recent review (Antonovics, Bradshaw, and Turner, 1971) suggests that knowledge relative to selective uptake is still fragmentary and that little is known about the role of emergent aquatics or woody species.

One experiment involving the use of sewage sludge as a soil conditioner on mine waste was successful in that the sludge provided plant nutrients while ameliorating the toxic conditions and improving the physical condition of the waste (Stearns, Kobriger, Levenson, and Rigger, 1974). In dredge spoil the organic content may serve to reduce some aspects of heavy metal toxicity. Another little known area deserving further attention concerns the activity of bacteria in influencing the solubility of certain metals.

DISCUSSION AND EVALUATION

It is amply evident that the nature of the substrate, the depth. timing, and duration of inundation, and the climatic factors of a particular season all influence the kind and behavior of plant species suitable for dredge dewatering. In addition, these factors may also affect the availability of nutrients through their influence on chemical reactions and biological activity. The drawdown of the water level results in several different effects, often including the rapid production of useful seed crops, the creation of conditions necessary for the establishment of plants which will serve as emergent cover after reflooding, and, perhaps most important, the changes in soil chemistry that lead to increased fertility after reflooding.

Most emergent wetland species (herbaceous or woody) will not germinate in any appreciable depth of water, but they do require a moist or wet surface with a continued supply of moisture for establishment. The weedy species associated with wet soils may be effective for dewatering, but it requires a moist, although not saturated, substrate for germination and development. Thus, the manipulation of the spoil surface to promote seed germination (after seed is made available) is an important consideration. The timing of the process is also important for establishing a stand. For maximum transpiration and for over-winter survival, plants need to begin development early in the growing season. The weedy species can develop extensive root systems and considerable above-ground biomass. The emergent aquatic plants can store carbohydrates in corms or rhizomes for a growth during the next growing season. The woody plants can develop a supporting root system and sufficient stem for rapid growth during the following year.

Species survival is directly influenced by the depth of inundation; some plants are capable of growth in several feet of water and others can adapt to only a few inches. Even the emergent aquatic plants adapted to continuous growth in water require that a portion of the stems and leaves be above water during most of the growing season. Most of the useful woody species can tolerate saturated conditions for considerable periods, and these are favored by aerobic conditions in the upper few inches of soil. In general, plants tolerate flooding more readily during the dormant season. The most effective period for dewatering will fall during the mid-portion of the growing season -- after leaves are fully developed and annual plants have reached their maximum size.

When harvesting methods are used, timing is again important. The time of harvest of the vegetation must be adapted to the particular species in question so as to neither remove the food reserves necessary for over-winter survival nor destroy the tops before materials used in the original spring growth have been replaced. On the other hand, if the purpose is to remove all possible biomass, harvest should proceed before the leaves fall and before major translocation of reserves to the root system takes place.

The economic potential of plants used for dewatering is considerable, although the deposition regime strongly influences the possibilities. Most uses will depend on the potential primary productivity, that is, the amount of organic matter that is fixed in a year under the particular growth conditions imposed. Table 9-8 shows the plants which seem to be feasible candidates for dredge spoil dewatering and which also have considerable potential for biomass production. The net primary production of emergent aquatic species often greatly exceeds production of crop species. Cattail is one of the more efficient producers. On wet soils the annual weedy species and woody plants may equal or surpass the production attained in a well tended corn field.

After primary production is known, the quality of the biomass may also be determined. Composition will vary in protein, fat, carbohydrate, tannin, cellulose, lignin, mineral nutrient, and heavy metal content. Cattail, for example, contains large quantities of extractable protein of a quality that is useful as a dietary supplement in human or non-ruminant diets, and

Table 9-8

Primary Production of Representative Communities

Plant Type	Location	Production Metric tons/hectare/year	Reference
Weed community	Wet soil in southern Michigan	10.1	Weigert and Evans, 1964
Weed community after drawdown (knotweed, beggars ticks, pigwood, reed canary grass, etc.)	Wet soil in southern Wisconsin	11.1	Klopatek, 1974
Reed canary grass	Saturated soil in southern Wisconsin	20.3	
Emergent aquatic species Cattail	Southern Wisconsin	24.0	
Sedge		10.7	
Rush		13.2	
Willow	Southern Wisconsin	19.0	
Corn for grain	Southern Wisconsin	10.0 - 12.0	Cottam, Howell, Stearns, and Kobriger, 1973
Alfalfa	Southern Wisconsin	9.5 - 12.5	

much crude protein is useful to ruminants. A knowledge of the composition of the biomass is essential in determining the potential wildlife useage, while the basic primary productivity values may serve to indicate the adaptation of the plant to the environment. Wildlife production depends on the plant growth and, to some extent, the success of invertebrates which feed on the plant.

From the geotechnical engineering point of view, the use of vegetation to stabilize dredge spoil may lead to the following improvements and shortcomings in the final landfill:

1. Since the growth of vegetation increases the number, length and surface area of capillaries, plants can transpire large quantities of water during the growing season. For some plants, the evapotranspiration rate can even exceed the rate of free-water surface evaporation. Moreover, due to the root extensions the drainage length may be reduced and the water loss may be distributed more uniformly with depth, thereby tending to reduce the creation of cracks and the formation of the top crust.

2. Due to the development of fibrous roots, the water loss through transpiration, and the root binding of soil particles, the shear strength of the rooted zone may be increased. Therefore, soil erosion by water or wind may be decreased.

3. Some plants (for example, bullrush) can absorb organic toxic compounds and metabolize them into carbon dioxide and water, whereas other plants readily accumulate metals in excess of the concentration in the soil. In this respect, the vegetation may play a major role in removing potentially toxic materials from the dredge spoil.

4. One of the shortcomings associated with the use of vegetation to dewater dredge spoil is the increase in organic content; although the deeper zones may be effectively dewatered by vegetation, the developed organic roots or rhizomes will extend deeper into the deposit. In this regard woody plants would seem to be somewhat prefereable to herbaceous species.

In general, vegetation may play an active role in the stabilization of dredge spoil on a long-term basis (that is, several years), but it may be relatively ineffective for short time considerations, since the dewatering rate and the strength increase are only affected by a small percentage (about 20% to 40%) of the original value. As previously discussed, the climatic conditions, inundation, timing, and seeding of spoil deposits cannot be easily controlled to assure the establishment and development of appropriate plant communities in an active dredge spoil disposal area. However, after disposal operations are complete at a site, vegetation is relatively easy to establish.

CONCLUSIONS

Based on a review of (a) the natural development of plant communities in poorly drained and submerged soils, (b) the establishment and growth of vegetation in wetlands, (c) the water consumption, mineral relations, and effects of pollutants on such plants, (d) an evaluation of the possible effectiveness of vegetation for dewatering and stabilizing dredge spoils, the following conclusions can be advanced.

1. Plants transpire large quantites of water during the growing season. The rate of water loss may equal or exceed that of free water evaporation, and the water loss will continue long after the surface of the spoil has become dry. Hence, vegetation can be used to dewater and partially consolidate dredge spoil.

2. The most likely plant communities for dredge spoil dewatering are the annual weed communities, the emergent aquatic communities, the shrub and wetland tree communities, and perhaps the wetland forage grasses. Dredge spoil may lend itself to several different types of vegetation, depending upon the water regime. Very wet sites may be best suited for semiaquatic species. In cases where the top few inches dry out sufficiently, the site may be well adapated for the rapid development of stands of annual weeds, which may later give way to other equally vigorous perennial herbs. Under suitable conditions the wet spoil may serve for the development of a shrub and willow complex.

3. The artificial establishment of plants appears feasible in most situations. However, the timing of deposition, frequency and thickness of lifts, length of inundation periods, and timing of inundation are important factors in the choice of plant species and in the establishment and survival or established vegetation.

4. Vegetation assimilates minerals and various organic toxic compounds, and much of this material can be removed by timely harvest. Mowing and harvest may also be used to remove most of the newly accumulated organic matter, which might otherwise cause problems when subsequent lifts of dredged material are deposited.

5. On suitable spoils vegetation may provide economically valuable products and in appropriate situations may be used for aesthetic enhancement of spoil sites.

6. Experience with the use of sewage sludge as a conditioner for mine wastes suggests that dredge spoil may also be used as a soil conditioner for strip-mine reclamation to provide plant nutrients and to ameliorate the toxic conditions through plant growth, thereby improving the physical condition of the wastes.

7. The oasis effect may enhance the use of in-land disposal areas, particularly if these areas adjoin parking lots or industrial sites.

CHAPTER 10

OTHER METHODS OF STABILIZATION

In addition to the chemical, evaporation, and transpiration methods of stabilization reviewed in the preceding chapters, there are numerous other methods of stabilization. Although some of these methods are expensive, they may be useful in some situations where no cheaper alternative is available or where external conditions (such as construction schedule) are demanding. Accordingly, various other available methods of stabilization are reviewed in this chapter.

COMPACTION

Compaction is one of the most effective methods for densifying and strengthening a soil. According to a survey on the use of soil stabilization in Australia (Ingles and Metcalf, 1973), more than half of all current stabilization is mechanical stabilization (compaction); of the remainder, cement stabilization accounts for 25 percent and lime for 9 percent. Included herein is a summary of a more detailed study by Krizek, Karadi, and Hummel (1973) on the strength and compressibility characteristics of compacted dredged materials. Six different materials were tested - three dredged materials, a bedding sand, Vicksburg clay, and Grundite; the latter three were included for comparison purposes. Three series of compaction tests were performed; the first was conducted to study the conventional moisture-density relationships for Standard Proctor compaction (ASTM D698); the second used the

Harvard Miniature apparatus (3 layers, 25 of 40 pounds tamps) (Wilson, 1950) to study the moisture-density relationships and stress-strain characteristics; and the third was performed with a specially designed mold to investigate the effect of compactive effort on the peak density and compressibility of the six materials tested.

The compaction data for the three dredged materials exhibit a response similar to that found for many ordinary soils; however, the dry densities are generally quite low and relatively sensitive to changes in water content, especially for the second series of tests conducted in the Harvard Miniature device. The results from both compaction procedures indicate that the coarsest dredged material exhibits a higher maximum dry density and a lower optimum water content. The higher densities obtained in the Harvard Miniature test can be explained in terms of greater compactive effort and the different compaction process (kneading rather than impact). The influence of compactive effort on the resulting dry density of each of the three dredged materials indicates that a 22-fold increase in the compactive effort increases the dry density about 30 percent (or about 20 pcf) in each case. Furthermore, increasing the compactive effort from Standard Proctor (12,400 ft-lb/ft^3) to Modified Proctor (56,300 ft-lb/ft^3) increased the dry density about 10 percent (or about 10 pcf). From a broad point of view, the density of a compacted dredged material may range from 60 to 90 pcf or more, depending on the type of compaction and the compactive effort. Since the dry density of a hydraulically placed dredged material is usually about 50 pcf, it becomes evident that the compaction of these materials to a density of 70 to 80 pcf would increase the capacity of a given disposal area by 40 to 60 percent, as well as stabilize the materials.

Unconsolidated-undrained triaxial test results show that the stress-strain curves manifest a characteristic strain-softening pattern, and most failures were associated with a system of cracks in the specimen, as described by Gau and Olson (1971). When interpreted in terms of the Mohr-Coulomb failure criterion, cohesion and friction values were found to range from 0.5 to 0.9 kg/cm^2 and 18 to 20 degrees, respectively. When these data compared with the results from a number of unconfined compression tests on "undisturbed" dredged samples from essentially the same location, cohesion values of the latter were found to be between 0 and 0.2 kg/cm^2, suggesting that the compaction of dredged materials will lead to a considerable improvement in their shear strength characteristics.

The compressibility data show that the settlement of compacted dredged material is dependent largely on its dry density. When compared with the bedding sand, Vicksburg clay, and Grundite, the dredged materials are found to exhibit a compressibility on the order of a loose sand, and significantly greater than a dense sand, the Vicksburg clay, and the Grundite. According to the test data, a 10-foot layer of dredged material similar to that tested in the laboratory, and compacted to a medium density (about 74 pcf) would undergo about 2 inches of settlement under an applied load of 1000 psf. Alternatively, if the dredged material were compacted to a loose density (about 64 pcf), a settlement of about 10 inches could be expected under the same load.

Dynamic consolidation appears to offer a technically feasible means for densifying in-situ layers of dredged materials. This method involves the placement of a drainage mat several feet thick above the dredgings in order to support the equipment and to provide an escape path for the water. The energy intensity developed by dropping a heavy weight (perhaps several tons) from a large height (perhaps 20 to 50 feet) causes extremely high pore water pressures with associated fractures in the soil mass, thereby facilitating rapid drainage and densification.

An additional series of compaction tests and unconfined compression tests were performed on lime and cement treated dredged materials to investigate the strength increase with respect to curing time. The test program involved the determination of the maximum dry density and the optimum water content by the Standard Proctor procedure for the materials with 0, 1, 2, 4, and 8 percent lime or cement. The number of tamps needed in the Harvard Miniature test to achieve the Standard Proctor maximum dry density at the Standard Proctor optimum water content was determined on the basis of a supplementary relation that was established between dry density and number of tamps per layer. Six samples were prepared by this procedure for each percentage of lime or cement. The samples were stored in a humid room at about 75°F, and the unconfined compressive strengths were determined at zero hours and after 2, 7, 14, 28, and 56 days.

The water contents and dry densities of the Harvard Miniature compacted samples are presented in Table 10-1. Comparing the data for lime treated and untreated samples at zero hours, indicates that the optimum water contents increased and the dry densities decreased with increasing percentages of lime. This is consistent with the results reported by Jin (1971) from some clay soils from Wisconsin. The same trend, to a lesser extent, was found for the cement treated non-cured specimens. Another point of interest is that for the 4 and 8 percent cement treated samples, the curing effect

Table 10-1

Water Content and Dry Density of Samples Compacted According to Harvard Miniature Procedure

Lime Treatment		Time (days) 0	2	7	14	28	56
1%	Water Content (%)	23.9	22.0	21.8	23.5	23.5	22.9
	Dry Density (pcf)	93.0	93.7	91.0	92.8	90.7	91.4
2%	Water Content (%)	26.6	22.9	22.9	-	23.0	22.8
	Dry Density (pcf)	89.8	91.9	91.7	-	91.1	91.5
4%	Water Content (%)	29.3	28.4	-	30.5	29.4	28.8
	Dry Density (pcf)	83.9	88.7	-	94.7	95.6	95.0
8%	Water Content (%)	30.0	29.0	29.8	31.0	30.7	29.9
	Dry Density (pcf)	86.4	88.3	90.1	94.8	96.1	95.8

Cement Treatment		Time (days) 0	2	7	14	28	56
1%	Water Content (%)	21.1	21.5	21.4	21.4	21.5	20.9
	Dry Density (pcf)	95.5	94.5	92.9	92.5	89.5	90.5
2%	Water Content (%)	21.0	21.0	21.0	-	21.0	20.6
	Dry Density (pcf)	95.0	94.1	93.7	-	91.9	90.0
4%	Water Content (%)	25.7	25.8	-	25.3	24.4	24.8
	Dry Density (pcf)	85.8	90.6	-	91.4	97.0	95.2
8%	Water Content (%)	25.3	25.5	26.0	25.7	25.4	25.2
	Dry Density (pcf)	91.3	94.5	94.9	100.4	102.6	102.9

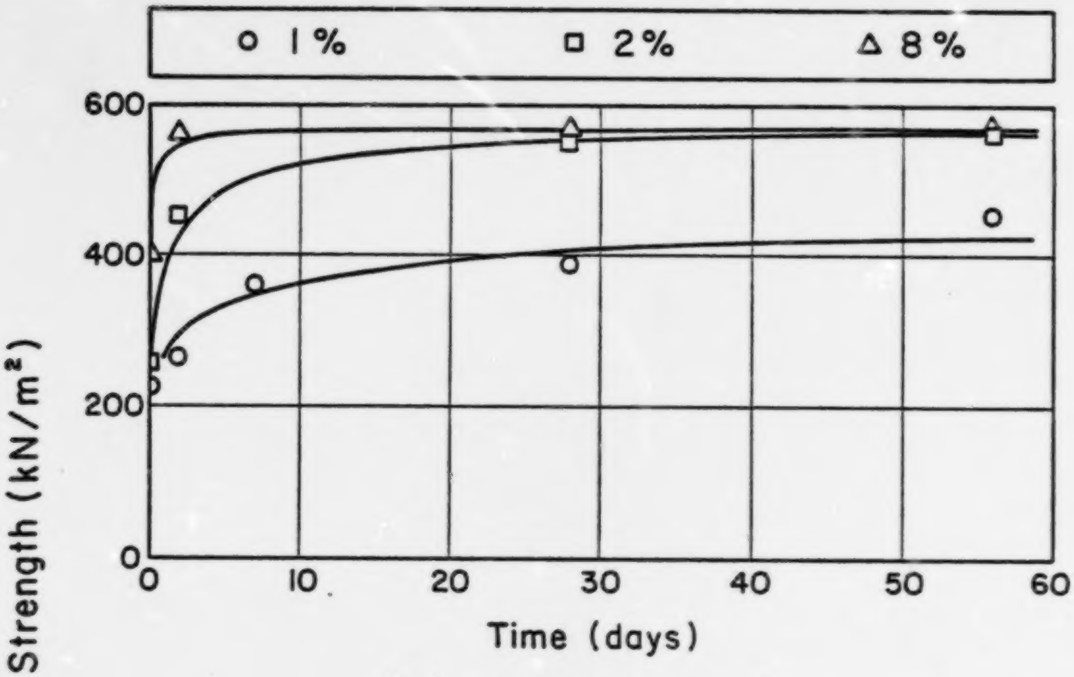
Note: Untreated samples had an initial water content of 21.5% and an initial dry density of 94.4 pcf.

tends to shrink or to densify the compacted samples up to 10 percent after 28 days. This is consistent with observations that concrete with low proportions of sand tends to crack. The same trend, but to a lesser extent, was observed for the materials with 2, 4, and 8 percent of lime. However, the opposite effect was found for the specimens with 1 and 2 percent cement and 1 percent lime. This may be due to hydration and flocculation effects causing the sample to swell during the curing process.

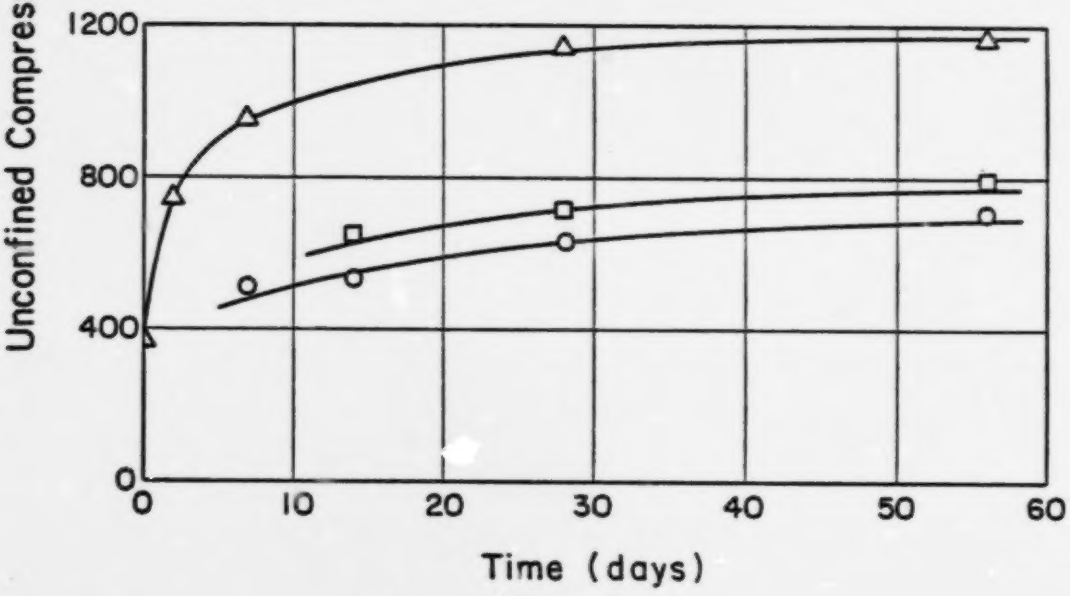
The erratic results found for the unconfined compressive strengths of these samples may be due to (a) the difficulty of preparing homogeneous samples and (b) the fact that the optimum moisture content for maximum dry density and that for maximum unconfined compressive strength may not necessarily be the same, as reported by Davidson, Pitre, Mateos, and George (1962). Therefore, deviations in the optimum moisture contents for maximum dry density may cause considerable differences in the maximum unconfined compressive strengths of the Harvard Miniature compacted samples. However, some reliable and representative data on the change in the unconfined compressive strength of compacted samples with curing time are presented in Figure 10-1. From this figure and other data available in Table 6-1, the following observations can be made:

(a) The unconfined compressive strengths for the non-cured lime or cement treated and untreated compacted samples seem to be approximately the same (about 2 to 3 kg/cm^2).

(b) Although the lower percentages of lime or cement may result in swelling or reduced density, the unconfined compressive strengths of the treated samples always increased with curing time.



(a) Lime Treatment



(b) Cement Treatment

Figure 10-1. Unconfined Compactive Strength of Compacted Sample versus Curing Time

(c) About 70 percent of the 28 day strength is reached after two days curing time.

(d) The unconfined compressive strengths of lime treated compacted samples increase with increased percentages of lime and curing time; these data are comparable with that from similar tests discussed in Chapter 6. According to the data in Figure 10-1a, 2 percent lime yields strength gains similar to those obtained for 8 percent lime.

(e) The unconfined compressive strengths of the samples treated with 8 percent cement increased four-fold over those for untreated samples after 14 days of curing; this is likely due to a combination of the fine cement particles filling the finer pores during compaction, possolanic reactions, and shrinkage effects. The strength increases almost linearly with cement content.

In comparing lime and cement treatments, Ingles and Metcalf (1973) state that the addition of either lime or cement to a soil with inadequate mechanical stability will improve strength, bearing capacity, and resistance to water-softening. However, in clay soils lime will often cause rapid changes in plasticity, and this effect would "dry out" the soil. This is the basis for the use of lime treatment as a construction expedient or for pre-treatment prior to cement treatment. Lime treatment is more tolerant of construction delay than cement treatment, and it is more suitable for clay soils. In short, both lime and cement stabilization with compaction can increase the strength to as much as 2 to 4 times that of untreated dredged material. At higher contents (4 to 8 percent) lime or cement may cause shrinkage cracks. However, the appicability of these methods depends on compaction efficiency (in-situ water content, depth of the slurry, and suitable machinery) and economic considerations.

ELECTRO-OSMOSIS

Electro-osmotic dewatering and stabilization has been used fairly extensively in Europe but to only a limited extent in the United States. For certain fine-grained soils which cannot be effectively drained by gravity methods, it offers outstanding advantages. However, since it is effective only for a narrow range of soils, it should be used only after evaluating the effectiveness of the method on the proposed soils. Krizek, Karadi, and Hummel (1973) reported on a study of four typical dredged materials which were subjected to two different electrical gradients, as well as gravity effects alone. The effects of this treatment on the dewatering rate and the improvement of the engineering characteristics of dredged materials were studied.

In an attempt to simulate field conditions, tests were conducted to allow uniform consolidation of the sample under a pressure equal to approximately ten feet of overburden ($0.6\ \mathrm{kg/cm^2}$) and a simultaneous application of a potential difference across the ends of the sample. Initial electrical gradients of one-half and one volt per centimeter of initial sample height were selected as typical of values which have been used successfully in previous field applications of electro-osmosis, and a reference test with zero electrical gradient was conducted on each material. All samples were drained at both the top and bottom surfaces but the electrical gradient always induced flow toward the bottom. Leachate samples were collected and subjected to chemical analyses. After the elctro-osmosis portion of the test was completed, the consolidated sample was subjected to vane shear tests and a conventional consolidation test. Tests for organic content, Atterberg limits, and chemical constituents were performed to determine effects of electro-osmosis.

Previous experience indicates that electro-osmosis would be expected to accelerate the dewatering and consolidation of these materials, thereby producing denser materials with higher strengths; these expectations were met in this test program. The test data indicate that an increase in the electrical gradient causes a substantial increase in the amount of fluid drained. The higher gradient produced its major effect in a shorter period of time than the lower gradient. The current decreases as the rate of fluid flow decreases. Values for the electro-osmotic coefficient of permeability were found to be of the same order of magnitude as those which characterize a large variety of soils (5×10^{-5} cm/sec per volt/cm).

The specimens subjected to no electrical treatment showed essentially no change in moisture content with depth, whereas the electrically treated specimens demonstrated a marked decrease in moisture content at the top of the specimen with relatively larger moisture contents toward the bottom. The larger gradients yielded lower water contents in all materials at all depths. However, the Atterberg limits and associated indices show that the electrical treatment produced no noticeable variations from those of the untreated material. Although the preconsolidation stress generally increased with increasing values of the electrical gradient, the compression index is relatively constant for a given material, regardless of the amount of electrical treatment imposed. General trends of decreasing shear strength with decreasing electrical gradient and with increasing depth from the top of the sample can be noted. However, the average shear strength was increased considerably by electrical treatment in all of the dredged materials. Table 10-2 lists several of the more important properties of the dredged materials in order to better evaluate the effects of the electrical treatment. These data show a large portion of the percentage change in dry density resulted from the applied consolidation pressure (0.6 kg/cm^2) and not from the electrical gradient. However, the increased average shear strength probably resulted from the electrical treatment, very likely due to its effects on changing the soil structure and increasing the bond forces of the clay particles.

The major chemical effects of electro-osmosis are probably due to two principal causes - the loss of ions to the leachate and the loss of compounds (for example, ammonia nitrogen) in the generated gases. As expected, there was a noticeable increase in the total solids content in the leachates from the materials subjected to electrical gradients. A similar trend in the volatile solids content in the leachate was not so well defined; this is probably due to the increased generation of gases with the larger gradients and the difficulty in obtaining a truly representative sample of the leachate for chemical analysis. The electrical treatment had a pronounced effect on the concentrations of ammonia nitrogen. Smaller amounts of ammonia nitrogen remained in the sediments subjected to the larger gradients; this is due to the fact that large amounts were removed with the leachate and probably to the generation and release of gases. The losses of ions from the sediments subjected to electrical treatments are reflected in gains for the same ions in the respective leachates, and the concentration of these ions increased as the gradient increased. A comparison of the test data for potassium and calcium from successive leachates for one material indicates a general

T-10-2

Table 10-2

Summary of Parameters for Electro-osmosis Tests

Sample	Electrical Gradient (volt/cm)	Initial Density (gm/cc)		Final Density (gm/cc)		Final Height / Initial Height	Final Void Ratio	Change in Dry Density %	Total Energy Consumed (watt-hours)	Average Shear Strength (psf)
		Wet	Dry	Wet	Dry					
C22TO	0	1.38	0.58	1.56	0.98	0.61	1.66	69	0	430
	½	1.36	0.57	1.66	1.11	0.53	1.36	95	43	1130
	1	1.33	0.56	1.65	1.15	0.49	1.21	105	154	2010
C27MM	0	1.31	0.54	1.53	0.94	0.58	1.81	74	0	880
	½	1.33	0.55	1.54	1.00	0.54	1.60	82	26	1710
	1	1.36	0.56	1.53	1.04	0.54	1.35	86	97	3470
D1DM	0	1.43	0.72	1.74	1.15	0.66	1.43	60	0	530
	½	1.44	0.72	1.60	1.10	0.64	1.28	53	86	1400
	1	1.47	0.74	1.67	1.16	0.64	1.23	57	114	1610
D4CO	0	1.40	0.65	1.71	1.14	0.57	1.53	75	0	560
	½	1.42	0.65	1.73	1.24	0.53	1.28	91	47	2650
	1	1.41	0.65	1.69	1.23	0.51	1.26	89	115	2470

increase in concentration with the progress of dewatering. The decreases in the concentration of exchangeable sodium and potassium ions in the sediment again reflect the loss of these ions to the leachates, but the effects on calcium are not so pronounced. The pH values of the leachates generally increased from 8.5 to about 12 as the elctrical gradient increased.

For the series of tests described, about one-half of the total energy was lost in each case, and this is attributable primarily to electrode corrosion and heat generation. In brief, electro-osmosis can significantly increase the volume of fluid drained from dredged sediments, and it can accelerate the rate of dewatering with associated decrease in water content and void ratio and increase in shear strength. The Atterberg limits and the conventional consolidation characteristics are not significantly affected by the electrical treatment. However, the use of electro-osmosis may increase the amount of ions leached from the sediment.

In their study of electro-harding, Ingles and Metcalf (1973) found that, if a corrodable aluminum [illegible] is used, the electrolytic attack on the anode provides a continuing supply of aluminum ions, which migrate towards the cathode under the potential gradient, displacing cations of lesser valence from the clay soils (for example, sodium). The aluminum clay thus formed has greater shear strength, lower swelling potential, and other desirable properties. However, electro-harding has not yet had sufficient practical use to allow a proper evaluation. Where power is cheap, it may offer a convenient method of deep stabilization. It is especially well suited to fully saturated materials, (that is, clays and silts below a water table). The intermittent application of electro-osmosis to increase the current efficiency has also been reported in the literature; this possibility should be studied to aid in assessing its economical application to the problem of dewatering dredged materials.

VACUUM DEWATERING

Vacuum drainage is one of the methods that can be used to accelerate the consolidation of the dredged materials in a disposal area. The creation of a partial vacuum beneath the dredged materials will enhance consolidation by lowering the water table, increasing the effective weight, and adding a partial atmospheric pressure to the surface of the soil. The vacuum system could be installed in a sand blanket that was laid prior to filling the area with dredged materials. The sand blanket may cover the entire site or only portions of the site where it would be most beneficial. As a result of their investigation of dewatering by electro-osmosis, gravity drainage, and vacuum drainage, Krizek, Karadi, and Hummel (1973) proposed a dewatering bin which had the possibility of combining all three effects to accelerate the dewatering process. Dredged materials could be placed into the bin and dewatered rapidly, after which the relatively dry materials could be moved into large open areas and placed in thin lifts to take advantage of evaporation and/or compaction.

Along this same line, Maurer (1973) conducted model studies of the consolidation process for dredged spoil both with and without the application of a vacuum. Comparisons were made by varying the sediment thickness and intensity of the vacuum. The apparatus used was a rectangular tank (48 inches by 20 inches and 48 inches high) constructed of 5/8 inch plexiglas. A graded filter 6.25 inches thick was placed in the bottom of the tank, and a number 80 wire mesh covered the graded filter. A 2 inch by 3/16 inch slotted tube 1.25 inches in diameter and with one end open to the outside was placed along the bottom centerline of the tank. During vacuum drainage tests the tube was connected to a pump which created a vacuum in the sand filter. Due to the expected low rates of drainage, the test tank was covered with a plastic sheet and was housed in a humid room. To measure the amount of water tension created in the dredged material when a vacuum was applied, tensiometers were installed in the sediment at various locations and depths.

These tests were divided into three groups, based on the final height (2, 4, and 6 inches) of the dredged sediment during the gravity drainage tests. The vacuum employed on these groups were 0, 9.5, 11.5, and 18 inches of mercury. Representative samples of dredged material were placed in the test tank and thoroughly mixed. The drainage tube was opened to either the atmosphere or the vacuum source, allowing water to drain. When the water had completely drained, the vacuum below the sediment was no longer sealed from the atmosphere because cracks developed during testing. As the sediment height and water level dropped, their respective heights were measured by graduated scales fastened to the sides of the tank. The water loss during drainage was measured by weighing the leachate collected. Tensiometer readings were taken during the tests, and samples of the sediment were taken for water content determinations. Vane shear tests were conducted on the dredged material near the surface and near the bottom of the layer.

The results indicated that, when the test began and the solid material started to settle, a zone of relatively clear water formed above the sediment. As drainage continued, the sediment densified.

For longer times, however, the sediment thickness remained constant as the rest of the water drained. When the water surface reached the sediment surface, the sediment thickness again decreased until it reached a new equilibrium. The amount of time required for drainage increased with the thickness of material. For a 6 inch layer of sediment and gravity flow only, drainage took more than 30 days. The drainage amounts after one day of applied vacuum were up to 5 times as great as for gravity alone. However, this increase is attributed to cracks which formed in the sediment and/or between the sediment and the tank wall, thereby allowing water to drain without flowing through the sediment. By keeping the applied vacuum relatively constant, the water tension in the sediment continued to increase with time. The tests were terminated before the water tension reached equilibrium. At the end of the test about one-half of the applied vacuum was measured on the tensiometers in the lower portion of the sediment; perhaps even greater values of water tension could be reached if the vacuum could be applied for greater lengths of time.

Within a relatively short time (about 6 days), the water content and dry density in the sediments subjected to vacuum drainage tests reached constant values, indicating that consolidation and drainage were essentially complete. The final water contents and dry densities of the vacuum drained sediments were 0 to 10 percent less and 0 to 14 percent greater, respectively, than those of the gravity drained sediments. In both vacuum and gravity drainage tests, the shear strength at the bottom of the sediment was about double the strength near the surface. The coefficient of permeability in the gravity drainage tests dropped from 13.4×10^{-6} cm/sec to 2.54×10^{-6} cm/sec as the thickness increased from 2 inches to 6 inches. In short, the greatest advantage of vacuum drainage is the accelerated rate of dewatering that is realized in the dredged materials. The final water contents, dry densities, and shear strengths resulting from vacuum drainage and gravity drainage were only slightly different.

Halton, Loughney, and Winter (1965) discuss a vacuum dewatering case history which was perhaps the first large scale application of a high vacuum executed on a firm price basis to consolidate a compressible clay soil. The site was a 2500 foot by 600 foot runway area at the Philadelphia International Airport. The soil conditions consisted of 5 to 10 feet of hydraulically deposited clay and silt from river dredging of recent years. Below the dredged material was 10 to 15 feet of soft clayey silt and silty clay. Beneath these compressible layers was over 100 feet of sand and gravel. Deep wells were installed around the perimeter of the stabilization area at approximately 600 feet on centers. The wells consisted of 12-inch diameter casings and screens, with 20 feet of screen below the bottom of each casing and 5 feet of screen immediately below the compressible layer. The casings were placed in 30-inch drilled holes packed with gravel to the top of the sand and gravel stratum and sealed with bentonite above that elevation.

As the groundwater was lowered, the air beneath the compressible soil was removed by vacuum pumps connected to the well casings. Leaks through the ground surface were located by the noise caused by the air entering the opening; they were then plugged with bentonite. A fifteen inch (mercury) vacuum was maintained for 18 calendar days. The anticipated settlements were obtained everywhere except at two of the twenty-two settlement plates. Results show that the majority of the settlement realized before paving was a result of the vacuum and dewatering stabilization treatment. In short, this project demonstrated that, where appropriate soil conditions exist, a high vacuum can be developed and maintained over a large area and settlement and strengthening of compressible soil strata will occur.

SPECIAL TECHNIQUES OF STABILIZATION

Laboratory studies of means for changing soil properties and the search for useful applications of diverse industrial and trade wastes have led to many proposed techniques for soil stabilization. In commercial practice at the present time no additive has yet been able to supplant the volume usage of the three major additives -- lime, cement, and bitumen. Nevertheless, some alternative soil stabilizers do appear to have useful applications in certain special circumstances. Presented herein are some techniques of stabilization which may have potential usefulness in dredged material landfills.

Quicklime Expansion Pressure

The technique of quicklime expansion pressure stabilization was developed by Chao and Chiu (1963). It is based on the substantial density difference between quicklime and hydrated lime (3.3 versus 2.2); this results in a high volumetric expansion during hydration. When this expansion is constrained, a high pressure is exerted on the surrounding soil and lateral consolidation is induced. The advantage of the lime system is that both reactants and products are readily permeable to water; thus, the reaction is able to proceed to completion and develop the full expansion force. Although other materials (for example, calcium sulfate, sodium sulfate, sodium carbonate, and bentonite) have a similar hydration effect, they produce either soluble or self-sealing products after hydration; hence, they are not as useful as quicklime. The expansion of quicklime can be utilized for soil stabilization in two ways -- either as closely spaced deep piles or trenches, where a lateral consolidation is desired, or in thin horizontal sandwich layers (Yamanouchi and Miura, 1967) to accelerate vertical consolidation. Although both methods have been used in the field, one disadvantage is the need for special equipment; however, an advantage is the ability to stabilize saturated fine silts.

Freezing

Penman and VanEs (1973) reported on freezing sludge to reduce disposal costs. The city of Winnipeg (population, 550,000), Manitoba, Canada, disposes of its digested sewage sludge by pumping it to seven 4-acre, 5 foot (1.5 meter) deep drying beds where solid-liquid separation takes place. Two layers form, and the top layer (supernatant) is drawn off into a holding pond where it is pumped back to the activated sludge plant inlet for treatment. The drying beds are used in rotation once every seven weeks. This operation continues until a 2 foot (0.6 meter) deep layer of sludge has accumulated on the bed bottom in the fall. Removal of the supernatant leaves a sludge layer with a solids concentration of about 20 percent. The beds are then allowed to freeze until they can support earth moving equipment; then, the sludge is ripped up and removed to a stockpile or trucked to nearby farms and spread on cropland. Underdrains in the sludge drying beds have been tried,but the drain pipes tended to become clogged with sludge and problems arise when the frozen sludge was ripped up. In this part of Canada 12 to 15 feet (3.6 to 4.6 meters) of impermeable clay often occurs naturally beneath the lagoon bottoms. Such conditions are favorable to the effective handling of frozen sludges (that is, there are no drain pipes to interfere with the removal operation, although the drainage is, of course, inhibited) and the clay layer acts as a filter to reduce the concentrations of contaminants entering the groundwater (periodic tests of water drawn from wells in the area indicated no pollution from sludge leachates). Operating costs for this technique are less than $1 per dry tone of sludge, including land, ripping, excavating, piping, pumps, trucking (within a 4 mile radius), and spreading; this is far cheaper than all competitive processes. This technique may be of interest in the northern United States, where winters are sufficiently cold to make it technically possible.

Alternatively, natural frost action may afford a feasible technique for accelerating the consolidation of fine-grained dredged material and increasing its dry density. If successful, this would serve to increase both the shear strength of the in-situ material and the capacity of the diked containment area. Advantage could possibly be taken of the characteristics of the freezing front to extract water from deeper within the fill layer and draw it closer to the surface. Also, there may be situations in which advantage could be taken of the frozen surface layer to place surcharge material, which would enhance consolidation of the underlying strata. Although no information on such a procedure is apparently available at this time (1974), the idea may justify further investigation.

Hydraulic Fills of Cohesionless Dredged Materials

Very frequently, dredged materials consist of cohesionless sandy soils, which are sometimes placed hydraulically. On the basis of the literature and their experience with the placement and compaction of numerous hydraulic sand fills, Turnbull and Mansur (1973) reported that a relative density of 50 to 60% can be obtained with no compaction for well-controlled hydraulic fills containing less than 10% fines. Some of the requirements for a well-controlled hydraulic fill are:

(a) The water table must be well below the surface of the fill so that there is downward drainage at all times.

(b) Material must not be bulldozed into low places without subsequent sluicing; otherwise, low densities will result.

(c) A uniform flow must be maintained over the fill surface by use of bulldozers and shear boards to direct the flow of water.

(d) Deposition into pools of water must be prevented in order to eliminate the accumulation of fines and associated low densities.

All hydraulic fill placed under water, other than as described above, will require some form of compaction to bring it to a stable density.

An article entitled in the "First Offshore Runway Grows 30,000 Cubic Yards Daily" in the July 4, 1974 issue of Engineering New Record describes a runway that is being constructed by hydraulic fill procedures off shore of the Honolulu International Airport. At some points construction advances over 100 foot a day toward the ultimate fill length of 14,000 feet. Since late 1973, an electric powered, 36 inch (0.92 meter) hydraulic dredge has placed nearly 25 percent of the 19.1 million cubic yards of coral fill. The dredge spews the granulated material in slurry form (15 percent solids) across the 800 acre site at a rate of 50,000 gallons per minute. The dredged material flows into a completely diked areas that serve as settling basins controlled by weirs, so that the slurry does not cause excessive turbidity throughout the lagoon. With a 14,000 horse-power pump, the dredge distributes fill through a single line that splits into three discharge heads that crawler tractors shift about with pipelaying booms.

Structural coral, not more than 15 percent of which may pass a No. 200 sieve, goes into all sections to be paved. With the placement of enough to allow two cubic-yard scrapers room to maneuver, shuttling of the structural material aside was started, down to an elevation of 3 feet, so that a 60-ton roller could proofroll it. Then, after placing the set-aside material in 8 inch layers, it was compacted to 95 percent of maximum density (article does not indicate whether Standard or Modified Proctor test was used). An aggregate base course 18 inches deep will cover the fill to support the runway, which will be 10 feet above sea level. The asphaltic concrete strip will be 200 feet wide and 5 inches thick with 50 foot shoulders. Another 6 inches of asphalt will be laid on the runway after five years of operation; this will allow any differential settlements to be smoothed.

CONCLUSIONS

Since each particular location and proposed type of development presents a separate engineering problem that requires individual study, none of the stabilizers or methods can be characterized as the best solution for all areas. Sometimes a combination of two or more methods can offer the best solution; for example, if lime and compaction are combined, the strength of the treated sediment can reach as high as two to four times that of its non-stabilized strength. In general, the optimum stabilization method is dependent largely on the proposed development of the land. Therefore, the following conclusions address both the field application of each method and the limitations imposed by land development:

1. Since the compaction is the most common method used to strengthen soils, and since test results show that the compaction characteristics of dredged materials exhibit a response similar to that of ordinary silty soils, it follows that compaction is very effective for stabilizing dredged materials, provided the initial strength of the sediment is high enough to withstand the loads imposed by the compaction equipment and provided the thickness of each lift is sufficiently thin to prevent excessive sinking of the equipment. Alternatively, dynamic consolidation seems ideally suited for densifying

dredgings under the conditions that prevail in many disposal landfills. The strength of the compacted dredged material can be further increased by prior lime or cement treatment. If the site has a good thick sublayer, it can probably be developed as a light industrial area.

2. Electro-osmosis is best suited for stabilizing saturated silty sediments. Although the water content and void ratio are decreased and the shear strength is increased by this method, the ultimate strength increase is only moderate. Further electro-hardening with corrodable aluminum electrodes may increase the strength, but the method requires more field study. Sites treated in this manner are likely candidates for development as residential or park areas.

3. Vacuum drainage is most useful for deep stabilization when a suitable substrata are present. In any case, the induced consolidation pressure cannot exceed one atmosphere on the ground surface. Based on model test results, the strength can attain only low to medium levels. Because of the sealing problem associated with the development of vertical cracks, this method is not applicable for stabilizing dredged sediments in a diked containment area.

4. Of the special techniques of stabilization,quicklime expansion pressure stabilization has excellent potential for application to stabilization soft surface sediments. However, the installation equipment, as well as the diameter and spacing of the quicklime piles, requires further investigation. After stabilization, the site may probably be developed as residential or park areas. Freezing stabilization is merely another disposal method that is applicable in areas with cold weather and nearby farmland where the sediment can be used as fertilizer.

5. In general, there is no need to stabilize cohesionless hydraulically dredged materials, provided the water table is well below the surface of the fill and a uniform flow is maintained. However, if the area is developed for uses that require high strength, further treatment will usually be required.

CHAPTER 11

SYNTHESIS AND INTERPRETATION

Soil stabilization is the collective term for any physical, chemical, biological, or other method, or combination of such methods, employed to improve certain properties of a specific soil in a particular environment, thereby enabling the soil to serve as a better foundation or construction material. The main thrust of this investigation is to evaluate possible methods of stabilization to improve the engineering properties of soft dredged sediments that are deposited inside diked containment areas.

The first stage of the investigation included a review of previous work concerned with dredged materials and the literature related to general stabilization technology. Based on this review, it was found that dewatering is one of the most effective ways of improving the engineering properties of dredged materials. Several dewatering methods, such as ditching, sand drains, preloading, etc, have been proposed; although these methods are quite simple in principle, they can not be easily or economically applied in actual diked containment areas. Dewatering by drainage can be accelerated if the coefficient of permeability, k, of the dredged material is increased, and this may be accomplished by adding various chemicals. There are many examples illustrating the successful use of flocculants for waste materials treatment and for highway soil stabilization. Since the process of placing dredged spoil hydraulically causes a thorough mixing of the material, additives might be easily added as the dredgings enter the inflow pipe. A series of tests were conducted with various chemical additives to study their effects on drainage characteristics and on pollution retention.

Observations and field test results from four diked containment areas in Toledo, Ohio, showed that the effects of evaporation and transpiration may substantially accelerate the dewatering rate of the top few feet of the dredged sediments. Supplementary laboratory and field model tests were conducted to further evaluate the effects of evaporation on the engineering properties of dredged materials. In addition, a literature survey was conducted to assess the effects of transpiration by vegetation.

FRAMEWORK OF TEST PROGRAM

In the chemical stabilization program outlined in Figure 11-1, three main series of tests were conducted; these included flocculation-sedimentation tests, sedimentation-leaching tests, and repeated leaching tests. These three types of test were developed in successive stages, wherein the findings of the flocculation-sedimentation tests formed background for the sedimentation-leaching tests, the findings of which, in turn, constituted the basis for the repeated leaching tests.

The addition of a flocculating agent to a soil suspension causes a flocculation or joining together of fine-grained soil particles, thereby increasing the effective particle sizes of the material. These larger flocs then settle more rapidly from suspension to form a relatively large sediment volume. The admixture of flocculating agents to dredged

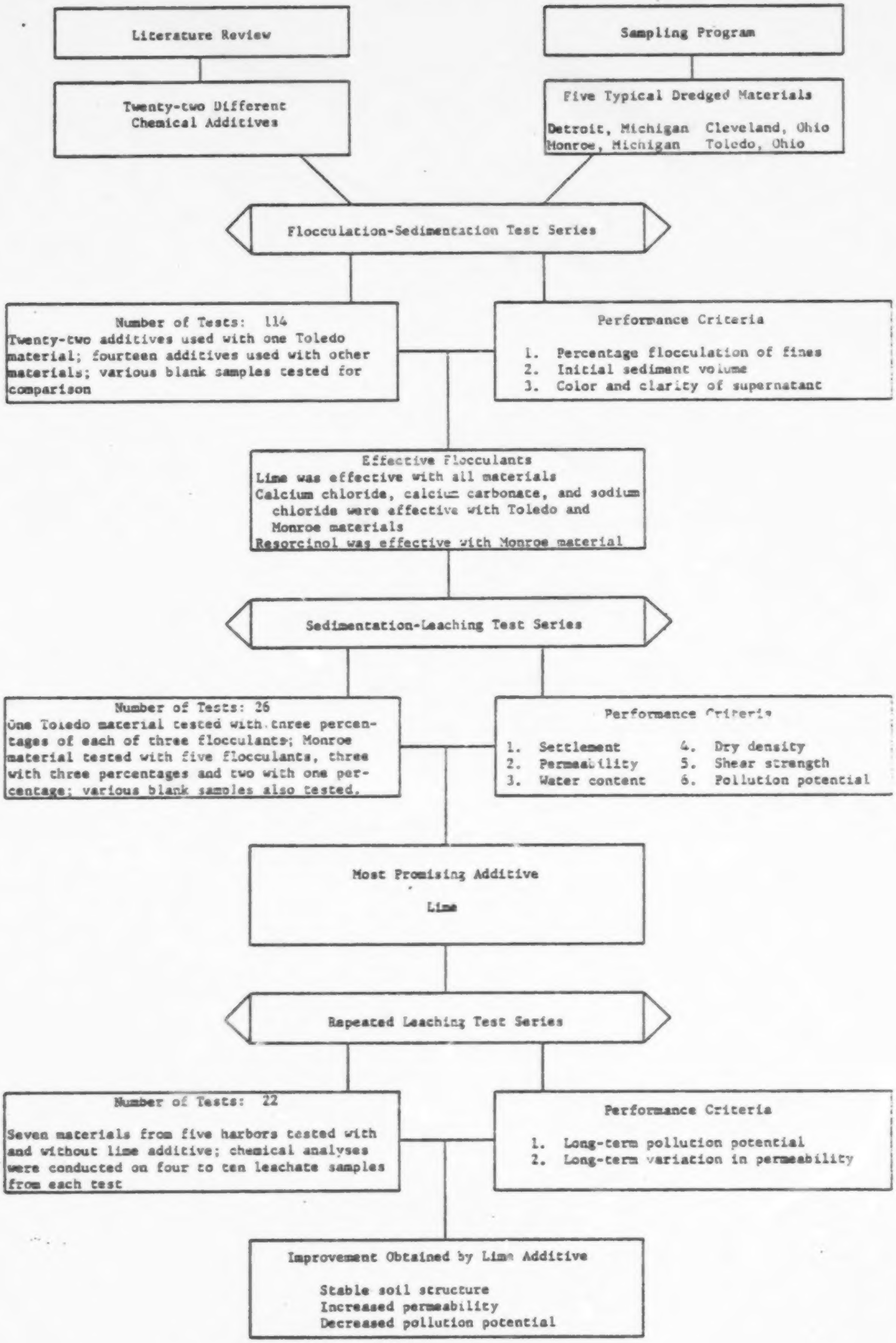

Literature Review
Twenty-two Different Chemical Additives
Sampling Program
Five Typical Dredged Materials
Detroit, Michigan Cleveland, Ohio
Monroe, Michigan Toledo, Ohio
Flocculation-Sedimentation Test Series
Number of Tests: 114
Twenty-two additives used with one Toledo material; fourteen additives used with other materials; various blank samples tested for comparison
Performance Criteria
1. Percentage flocculation of fines
2. Initial sediment volume
3. Color and clarity of supernatant
Effective Flocculants
Lime was effective with all materials
Calcium chloride, calcium carbonate, and sodium chloride were effective with Toledo and Monroe materials
Resorcinol was effective with Monroe material
Sedimentation-Leaching Test Series
Number of Tests: 26
One Toledo material tested with three percentages of each of three flocculants; Monroe material tested with five flocculants, three with three percentages and two with one percentage; various blank samples also tested.
Performance Criteria
1. Settlement
2. Permeability
3. Water content
4. Dry density
5. Shear strength
6. Pollution potential
Most Promising Additive
Lime
Repeated Leaching Test Series
Number of Tests: 22
Seven materials from five harbors tested with and without lime additive; chemical analyses were conducted on four to ten leachate samples from each test
Performance Criteria
1. Long-term pollution potential
2. Long-term variation in permeability
Improvement Obtained by Lime Additive
Stable soil structure
Increased permeability
Decreased pollution potential

Figure 11-1. Outline of Test Program for Chemical Stabilization of Dredged Materials

materials during the process of disposal into a diked containment area can effectively increase the sedimentation rate and consequently decrease the amount of suspended solids in the effluent water. In addition, the flocculation of suspended solids may cause increased retention of pollutants in the disposal area and further improvement in the quality of the effluent water.

A total of 114 individual flocculation-sedimentation tests were conducted with twenty-two different chemical additives that were selected on the basis of test results from previous non-related studies. Grain size distribution curves and sediment volume data were used to evaluate the effectiveness of the various chemical additives on the degree of flocculation and the sedimentation rate of suspended solids. The criteria for evaluating the flocculation effectiveness of these chemicals were (a) the percentage of fines that flocculated, (b) the initial sediment volume, and (c) the color and clarity of the supernatant. Once a slurry has settled in a diked containment area and the dewatering-consolidation process has begun, several forces (such as seepage forces, capillary forces, forces caused by vegetation, etc) act on the sediment. For sediments that are subjected to only their self-weight, the latter two forces are probably dominant in enhancing consolidation, particularly in top few feet of the fill.

Twenty-six sedimentation-leaching tests were performed with two typical dredged materials to study the effectiveness of chemical additives in stabilizing such materials. The shear strength and the corresponding water content were measured, the coefficient of permeability was calculated, and the water quality of the leachate was analyzed.

In addition, an associated sedimentation test without drainage was conducted to observe the sediment behavior with time and the effect of the seepage force. All of these parameters were used as criteria to judge the effectiveness of various chemical stabilization methods. These tests were performed in cylindrical sedimentation chambers 18 inches (45 cm) high and 3 inches (7.5 cm) in diameter with a porous stone at the bottom for drainage and an outlet to collect the leachate.

Twenty-two repeated leaching tests were conducted on various typical dredged materials with and without chemical additives to study the long-term pollution potential of the leachates; these tests were performed in chambers similar to those described above, except that they were 24 inches (60 cm) high and 6 inches (15 cm) in diameter. In addition, the hydraulic gradient was varied to assess its effect on the pollution potential of the leachates. Under some conditions a substantial volume of water may pass through the deposited sediments and enter the foundation soils underlying a diked containment area, and the possible pollution of the groundwater by these leachates could pose a problem. The contaminants carried by a leachate depend on the composition of the dredged material and the chemical additive, as well as on the physical, chemical, and biological activities that take place within the landfill. Since the repeated leaching tests conducted in this experimental program frequently lasted several months due to the low filtration capacity of the dredged materials, bio-chemical reactions might have taken place during the tests (however, only chemical analyses were conducted on the leachates) and such biologically induced changes might have the ability cause additional mobilization compared to a sterile system.

Evaporation is known to be a promising technique for the economical dewatering of dredged sediments within diked containment areas, and an investigation was therefore conducted to evaluate laboratory and field evaporation losses from dredged materials and the associated strength gains and water retention curves. A knowledge of the soil-water potential of dredged materials provides the background for a better understanding of the material behavior during the evaporation process. Three different series of laboratory evaporation tests were conducted. The purposes of the first series were (a) to study the rate of water loss from several different dredged materials and (b) to determine the effect of mixing on the rate of water loss. The second series of laboratory evaporation tests was directed toward (a) evaluating the influence of sample thickness and surface area on the rate of water loss, (b) observing crack sizes and crack patterns, and (c) determining shear strength gains in the drying soils. The objectives of the third series of tests were (a) to study the effect of lime (CaO) on the water loss, shear strength, deformation, and crack patterns of the sediments, (b) to obtain additional data to help in interpreting the results of the previous laboratory evaporation tests, and (c) to serve as a guideline for the interpretation of the field evaporation test data. All tests were performed either in a glass container 6 inches (15 cm) high and 6 inches (15 cm) in diameter or in plastic plans 18 inches (45 cm) by 13 inches (33 cm) in areal extent and 4 inches (10 cm) high; the average temperature and relative humidity were about 75°F and 35%, respectively.

Two series of field evaporation tests were conducted in the Toledo area. Both of these test programs were designed to study the strength and deformation behavior of dredged materials subjected to the climatic conditions at the Penn 7 disposal area (average temperature about 73°F; average relative humidity about 65%; and total precipitation about 9 inches (23 cm) during both test periods). Relatively small scate tests were used to obtain better control of sediment thickness, drainage conditions, and lime (CaO) treatment. In the first series twelve drums (22 inches (56 cm) in diameter and 35 inches (88 cm) in height) were used; five of these had perforated bottoms and sand filters to allow drainage during the test period, which began on August 1, 1973 and continued for 14 days. The second series of ten field evaporation tests was conducted at the same site and with the same drums, but greater sample depths were used and a longer test period of 113 days (August 5 through December 5, 1973) was allowed.

SYNTHESIS OF TEST RESULTS

Described in the following paragraphs are a synthesis of the results from the four test series conducted in this study and the work on dredged materials by other researchers. The major parameters of interest are leachate quantity and quality and dredged material permeability and strength.

Leachate Tests

For purposes of simplification, all data from the various tests on the leachate samples are compared to those of repeated leaching tests. The other tests include drainage, electro-osmosis, slurry consolidation, and sedimentation-leaching. Table 11-1 presents the results

Table 11-1 Reproduced from best available copy.

Chemical Analyses of Leachates from Drainage Tests

Sample	Total Solids	Total Volatile Solids	Total Suspended Solids	Total Volatile Suspended Solids	Turbidity	Acidity	Hydrogen Ion Concentration (pH)	Oxidation-Reduction Potential (Eh)	Dissolved Oxygen (DO)	Biological Oxygen Demand (BOD)	Chemical Oxygen Demand (COD)	Organic Nitrogen (N)	Ammonia (NH$_3$) Nitrogen (N)	Nitrite (NO$_2$) Nitrogen (N)	Nitrate (NO$_3$) Nitrogen (N)	Total Phosphate (PO$_4$)	Soluble Phosphate (PO$_4$)
	%	%	%	%	JTU	mg/gm		mv	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm
01DM-M	0.1681	0.0914	0.0126	0.0041	92		9.2	0.030		0.1090	0.672	0.0121	0.0356	0	0.0198	0.0061	0.0061
01DM-V	0.1734	0.0895	0.0003	0.0054	58		9.1	0.025		0.0662	0.586	0.0157	0.0291	0	0.0131	0.0020	
01DM-G	0.1318	0.0916	0.0126	0.0072				0.030		0.0409	0.309	0.0330	0.3359	0	0.0097	0.0017	
03TO-M	0.1294	0.0336	0.0506		100		8.8			0.0935	0.267			0	0.0073	0.0008	
03TO-V	0.1034	0.0326	0.0756	0.0091	130		8.5	0.025		0.0850	0.186	0.0011	0	0	0.0072	0.0015	
03TO-G	0.0751	0.0165	0.0145	0.0035	70		9.2	0.020		0.0505				0	0.0068	0.0008	
04CD-M	0.1952	0.0540	0.0246	0.0070	55		9.0	0.065		0.0566	0.349	0.0112	0.1537	0	0.0076	0.0033	
04CD-V	0.1381	0.0623	0.0065	0.0025	36		8.9	0.030		0.0675	0.315	0.0190	0.2532	0	0.0070	0.0061	
04CD-G	0.1210	0.0352	0.0168	0.0063	45		8.7	0.030		0.0656				0	0.0096	0.0041	

Sample	Grease	Hydrocarbons	Aluminum (Al)	Arsenic (As)	Calcium (Ca)	Copper (Cu)	Total Iron (Fe)	Soluble Iron (Fe)	Potassium (K)	Silica (SiO$_2$)	Sodium (Na)	Sulfide (S)	Cadmium (Cd)	Cyanide (CN)	Lead (Pb)	Mercury (Hg)	Phenolics
	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	mg/gm	µg/gm	µg/gm	µg/gm	µg/gm	µg/gm
01DM-M			0.030		0.0737	0.0117	0.185		0.022	0	0.200		0		0	0.0175	
01DM-V			0.030		0.0652	0.0063	0.185		0.040	0	0.100		0		0	0.0021	
01DM-G			0.030		0.0997	0.0061	0.115		0.038	0	0.120		0		5.5		
03TO-M			0.060		0.1090	0.0061	0.260		0.028	0	0.050		0		4.0	0.0037	
03TO-V			0.060		0.1040	0.0061	0.200		0.020	0	0.036		0		0	0.0016	
03TO-G			0.030		0.0870	0.0086	0.075		0.012	0	0.036		0		2.0		
04CD-M			0.060		0.0950	0.0093	0.390		0.063	0	0.240		0		4.0	0.0136	
04CD-V			0.060		0.0630	0.0150	0.200		0.050	0	0.200		0		5.5	0.0039	
04CD-G			0.015		0.0720	0.0110	0.280		0.072	0	0.150		0		4.0	0.0095	

Note: M - Vacuum drainage with a membrane for sealing
V - Vacuum drainage without a membrane for sealing
G - Gravity drainage alone

of chemical analyses on leachates from drainage tests; these data are expressed on a wet weight basis, but the units are different than those used for repeated leaching tests. These results show, in general, that the values increase in the order of gravity drainage alone (G), vacuum drainage (V), and vacuum drainage with a membrane (M); the observed differences are due mainly to increases in the hydraulic gradient. However, it is found that the concentrations of the various constituents for all of the leachates from drainage tests are of the same order of magnitude as those of the first or second time leachates from repeated leaching tests.

Table 11-2 summarizes the results of chemical analyses on leachates from electro-osmosis tests. There are noticable increases in the percentage of total solids with larger electrical gradients. The pH values of the leachates also increased considerably as the electrical gradient increased. The decreases in the concentration of exchangeable sodium and potassium ions in the sediments subjected to electrical treatment are reflected in gains for the same ions in the respective leachates as the electrical gradient increased; however, the effects on calcium ions are not so pronounced. When comparing these data to those of the repeated leaching tests, the concentrations of other constituents are of the same order of magnitude as those of the first or second time leachates from repeated leaching tests.

Table 11-3 gives the results of chemical analyses on leachates from slurry consolidation tests. As seen from this table, the chemical constituents of the leachates from the dredged sediments show a uniformity in the concentrations of certain ions in the leachates during

Table 11-2

Chemical Analyses of Leachates from Electro-osmosis Tests

Sample	Electrical Gradient (volt/cm)	Specimen Number	Total Solids (gm/l)	Total Volatile Solids (gm/l)	NH_3-N (mg/l)	pH	Al (mg/l)	Ca (mg/l)	Cu (mg/l)	Fe (mg/l)	K (mg/l)	Na (mg/l)
C22TO	0	1			132	8.9	0	102	0.35	0.19	12	290
		2	0.129		84	8.2	25	2000		14.00	87	260
	½	1	0.561		138	9.9	0	65	0.80	9.20	7	320
		2	1.849		246	12.4	0	550	0.70	8.30	20	530
		3	0.233		320	12.5	0	640		2.50	290	330
	1	1			172	12.1	12	340	0.85	9.30	15	360
		2	2.297		400	12.3	0	678	0.35	2.00	28	630
		3	0.257		456	12.6	26	5800		33.00	160	205
C27MM	0	1	0.607	0.129	46	8.1		13.8			13	39
		2	0.732	0.154	32	8.2		11.0			16	41
	1	1	0.539	0.105	115	11.4		0.5			15	90
		2	2.073	0.125	228	12.4		240			24	38
D1DM	0	1	0.988		132	7.9	0	340		0	120	900
		2			120	9.4						
	1	1	0.107		210	12.0	26	950		101.00	170	1170
		2			384	11.3						
D4CO	0	1 Bottom	0.703	0.252	255	8.6		12.5			18	97
		1 Top	0.760	0.289		8.4		5.8			18	100
		2	0.904	0.329	354	8.9		5.4			21	170
	1	1 Bottom	1.363	0.208	724	12.3		1.2			170	380
		1 Top	2.377	1.179		5.0		68			12	41
		2	1.574	0.109	1117	12.4		2.4			225	420

Table 11-3

Chemical Analyses of Leachates from Slurry Consolidation Tests

Sample	Effluent Specimen	Vertical Stress (psi)	Time (min)	Concentration in ppm					
				Pb	Cu	K	Na	Ca	Fe
C11TO	1	1	970	0	0.15	27	22	0	10
	2	4	7,416	0	0.85	27	21	8	--
	3	8	11,090	0	--	32	23	12	10
	4	16	32,603	0	--	27	26	28	--
C13TO	1	2	8,480	0	0.05	27	23	75	4.3
	2	2	11,320	0	0.03	27	21	75	12.2
	3	4	19,100	0.25	0.15	27	23	132	2.5
C15TO	1	4	1,360	0.25	0.03	18	25	95	2.7
C20TO	1	1	970	0	0.05	27	28	22	2.3
	2	8	11,090	0	--	27	--	12	2.5
	3	16	22,585	0	0	27	28	8	2.5
C22TO	1	1	970	0	6	25	30	4	--
	2	4	7,416	0	0	--	--	--	--
	3	8	11,090	0	--	27	--	50	--
	4	16	22,586	0	0	27	25	34	1
C27MM	1	2	1,460	0	0	14	27	50	2.8
	2	2	11,320	--	1	14	25	34	0.3
	3	4	19,100	0	0	14	27	75	2.8
	4	4	19,820	0	0	14	26	56	2.8
D9TO	1	2	8,480	0.25	0.01	18	22	75	2.5
	2	2	11,320	0	0.01	18	23	65	2.5
	3	4	19,100	0.25	0.03	22	23	95	80

the entire consolidation process. Furthermore, the concentrations of these ions are also in the same range as those from first or second time leachates from repeated leaching tests.

When comparing the data in Table 6-3 with that in Tables 7-3 and 7-4, the total solids content seems to increase significantly in the leachates from the sedimentation-leaching tests relative to the total solids content of the first or second time leachates from repeated leaching tests. This is due mainly to the fact that, for the sedimentation-leaching tests, the sedimentation and leaching occurred at the same time the fluid passed through the larger pores, whereas, for the repeated leaching tests, the sedimentation took place first and then the leaching process began. Also, some dissolved additives in the sedimentation-leaching tests also increased the total solids content. The same trends are also shown in the concentrations of other constitutents. Noticable increases in specific ion concentrations in the leachates were directly related to the additive and to treat the dredged material. However, the general increase in the concentrations of specific constituents do not have practical significance if more than a few feet of relatively uniform pervious clay overlays the bottom of the diked area; in this case, the sedimentation process would be essentially complete before significant quantities of leachates passed through the clay layer. As discussed in Chapter 7, the average results of the chemical analysis of the initial groundwater samples from the wells, are of the same order of magnitude as the first-time leachates from the repeated leaching tests. In general, it may be concluded that the leachate data from repeated leaching tests may represent data for leachates from other tests, except for the excessive removal of exchangeable ions from the sediment due to electro-osmosis effect and the increase in specific ions directly related to the additive that may have been used.

Based on the results from repeated leaching tests and related literature, the leachates of dredged materials in diked containment areas do not appear to cause any serious pollution problem; this is due in large part to the fact that the permeabilities of most clayey silt dredged sediments are very low compared to that of sanitary sludges, the natural ability of underlying soils to remove many contaminents, and the ability of groundwater to adequately dilute the relatively small amounts of contaminents that are leached from the solids are important factors to consider.

Permeability

A synthesis of data from several different types of laboratory and field tests on a variety of different untreated dredged materials is shown in Figure 11-2. The coefficient of permeability is seen to decrease from about 10^{-4} to 10^{-9} cm/sec as the void ratio decreases from approximately 10 to 1. The dredged materials with the highest void ratios ($2 < e < 10$) were tested by gravity drainage (sedimentation-leaching), and permeability coefficients on the order of 10^{-4} to 10^{-6} cm/sec were determined. For the vacuum drainage tests in which a partial vacuum was applied (thereby consolidating the sample somewhat and decreasing the void ratio), permeability values on the order of 10^{-6} to 10^{-7} cm/sec were obtained. Most void ratios for the slurry consolidated samples ranged from about 1 to 2, and the resulting

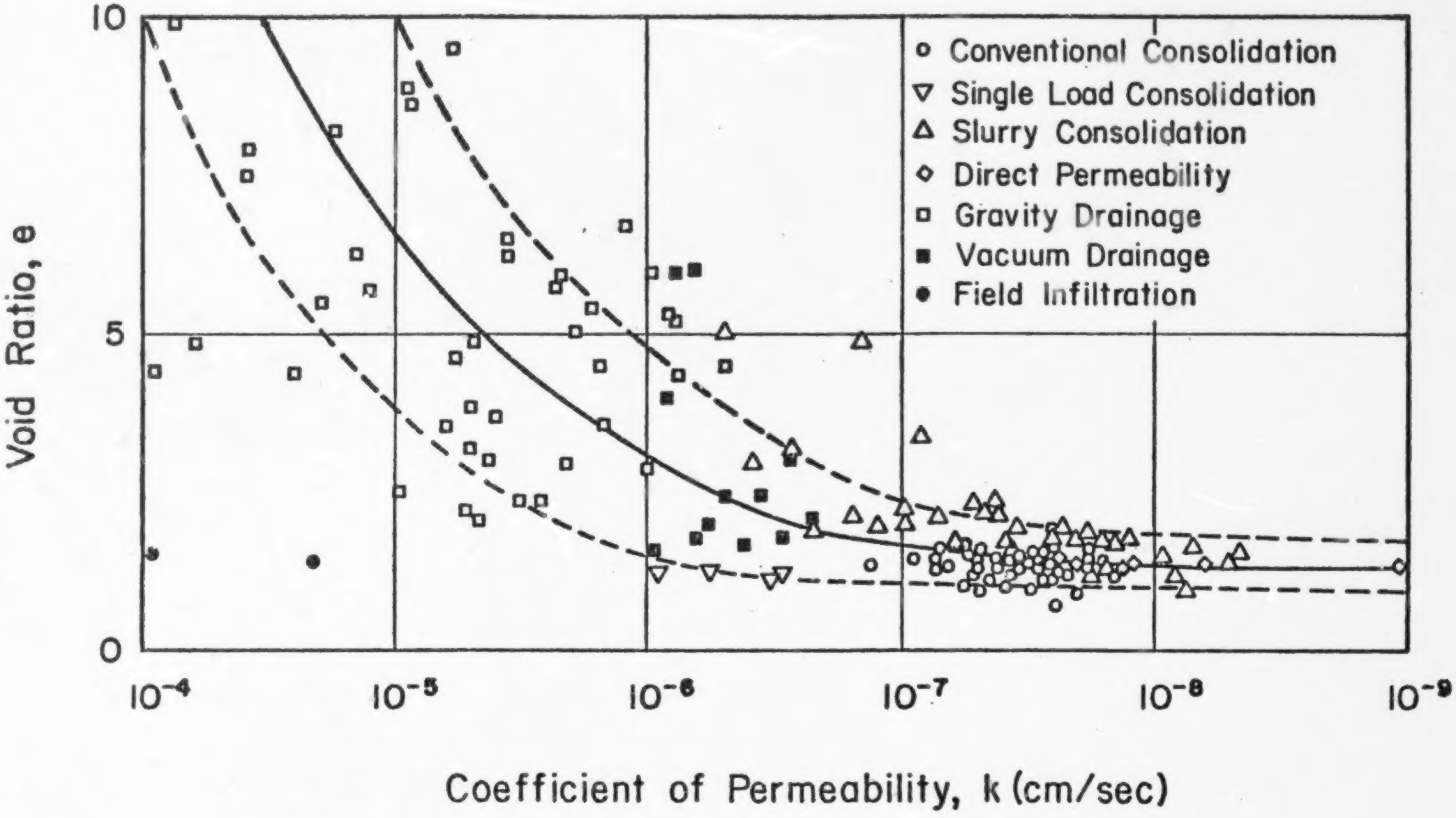


Figure 11-2. Effect of Void Ratio on Coefficient of Permeability

coefficients of permeability were approximately 10^{-7} to 10^{-8} cm/sec. Direct permeability tests, the single-load consolidation tests, and the conventional consolidation tests were conducted on samples with void ratios on the order of 1, and the associated permeability values lie mostly between 10^{-7} to 10^{-8} cm/sec.

Based on the mineralogy, organic content, Atterberg limits, and gradation of the dredged materials tested, they may be classified as fine-grained, organic soils (OH, according to the Unified Classification System), and their permeability and drainage characteristics are generally consistent with those associated with these types of soils. As expected, two in-situ field tests yielded much higher values for the permeability (10^{-4} to 10^{-5} cm/sec); this was probably due in large part to the seasonal stratifications associated with dormant periods during dredging seasons and to trapped gases created when poor drainage conditions prevailed. The electro-osmotic coefficient of permeability (Krizek, Karadi, and Hummel, 1973) was found to range from about 1.5×10^{-5} to 4.5×10^{-5} cm^2/volt-sec; this value is consistent with that found for a large variety of soils. Finally, based on test data from chemically treated samples in sedimentation-leaching and repeated leaching tests, it was found that the coefficient of permeability for the lime treated samples can be increased more than 10 fold when compared to that of untreated material; specifically, the coefficient of permeability ranged from 10^{-3} to 10^{-5} cm/sec for void ratios less than 3.5.

Strength

The strength of dredged materials is a major parameter in soil stabilization because it is directly related to the bearing capacity and stability of a landfill. Since there are no definite criteria for shear strength requirements for stabilized landfills, it is assumed herein for convenience of discussion (referring to the classification of clay according to its consistency; Terzaghi and Peck, 1967) that the shear strengths of dredged materials may be categorized into three ranges; these are 250 psf or less (low shear strength), 500 psf to 1000 psf (medium shear strength), and over 2000 psf (high shear strength). Within this framework it is easy to examine the limitations of each stabilization method and the potential usefulness of landfills after stabilization.

Based on field vane shear strengths of dredged sediments in the Toledo diked containment areas (Krizek, Karadi, and Hummel, 1973), it is found that almost all results lie in the low shear strength level, except for the top one to two feet of crust which has a low to medium level of shear strength due primarily to the effect of desiccation. However, this effect seems to be reversible, because those locations in the middle portion of the layer were at one time at the surface and subjected to desiccation. When these test locations were subsequently submerged by later dredging deposits, their shear strengths were reduced to the low level. This phenomenon may also show indirectly the importance of good surface drainage. However, an examination of the shear strength data from samples subjected to laboratory drainage tests (Krizek, Karadi, and Hummel, 1973; Maurer, 1973) shows that the effect of good drainage alone can not increase the shear strength of the sediment to the medium level. Furthermore, vacuum drainage was able to increase the shear strength of the sediment to the medium level only if the thickness of the sediment was greater than 1.5 feet; the increase in shear strength only pertains to the sediments below this depth.

The laboratory vane shear strength test data for samples from the slurry consolidometer (Krizek and Salem, 1974) show that, for samples consolidated to 4600 psf preconsolidation pressure with good drainage, a high shear strength level can be reached. In addition, strength data for the reference samples (no electrical gradient) from electro-osmosis tests (Krizek, Karadi, and Hummel, 1973) show that, for 1200 psf preconsolidation pressure and with good drainage, the shear strength of the sediment may reach the medium level. Therefore, it can be concluded that preloading together with good drainage is effective in strengthening dredged materials. On the other hand, with the application of an electrical gradient of about 1 volt/cm to the above mentioned sample, the shear strength can be increased to the high level. This phenomenon implies that the electro-osmotic effect is effective in increasing the strength of the sediment, provided that the sediment initially has a proper density (medium consistency and strength).

The vane shear strength results for sediment from the sedimentation-leaching tests show that, although the more promising chemical additives can effectively flocculate the sedimenting particles, they alone can not increase the strength of the sediment, even if good drainage is provided. This can be explained in terms of density; without adequate density, cementation effects can not act effectively. Further proof of this point can be seen from the strength increase of chemically treated compacted samples, which display a high shear strength level. Although compaction alone can increase the shear strength to the high level, effective chemical treatment can increase the strength by a factor of two or more. This means that the cementation reaction is more effective at higher densities.

The shear strength of the dredged sediments was one of the parameters emphasized in the evaporation test program. Although all laboratory samples (less than 6 inches in depth) ultimately reached very high shear strength levels in about 40 days, the samples in the field with good drainage only reached medium shear strength levels in about 50 days. This may be due to the thicker sample depth (20 inches), precipitation, and an initial high water content. For the undrained field samples the shear strengths were all in the low level category. A comparison between the shear strengths of laboratory and field lime-treated samples again shows the importance of density on strength increase; in particular, for samples with a sufficiently low density, such as that of field samples, the strengths show essentially no increase. Although there are no direct results of shear strength increase of dredged sediments subjected to field compaction, the limited data from laboratory tests suggests that compaction will lead to a considerable improvement in shear strength. However, the efficiency of field compaction is limited by the in-situ water content, depth of the slurry, availability of suitable machinery, and economic considerations.

DISCUSSION OF STABILIZATION METHODS

In the course of selecting a stabilization method or combination of methods, it is essential to understand the initial and desired final behavioral characteristics and engineering properties of the materials to be stabilized, as well as the suitability and limitations of each stabilization method. However, economic stabilization usually requires that as much advantage as possible be taken of natural phenomena, such as solar energy (evaporation and transpiration effects) and gravity (sedimentation, surcharge loading, and drainage effects). A dredging slurry placed hydraulically into a diked containment area may have a water content of 500% or more (equivalent to 15% or less solids). This can be readily reduced to about 100% to 150% by sedimentation if an adequate size retention basin is provided. In conjunction with this process, the effect of chemical additives were studied. Effective additives may increase the sedimentation rate and simultaneously remove more suspended solids from the supernatant, which would, of course, reduce the pollution potential of the effluent that is discharged over the weir. The improvement of the final engineering properties of the treated sediments were also evaluated.

Chemical Stabilization

The purposes of the chemical stabilization test programs reported herein were (a) to evaluate the flocculative effectiveness of chemical additives (flocculation and sedimentation tests), (b) to study the improvement in the engineering properties caused by the more promising chemical additives (sedimentation-leaching tests), and (c) to compare the pollution potential of the leachates from treated and untreated dredged sediments (repeated leaching tests). The following paragraphs summarize the major findings that were obtained from these three series of chemical stabilization tests. As mentioned previously, the parameters involved in each successive test sequence were selectively chosen from the results of the preceding series.

Based on a literature review, twenty-two different chemical additives were selected. Through flocculation-sedimentation tests on five dredged materials, it was found that calcium oxide and calcium chloride were effective flocculants for most of the dredged materials; the supernatans were colorless and clear for all of the samples tested. The chemicals o-nitrophenol, p-nitrophenol, and tri-nitrophenol were effective flocculants, but the supernatants, although clear, were yellow and pink in color. This visual pollution of the effluent and the toxicity of the chemicals make them undesirable as practical flocculating agents. Similarly, acetic acid, phosphoric acid, sulfuric acid, nitric acid, hydrochloric acid, and aluminum sulfate were all found to be effective flocculants, but the supernatants were cloudy and had a brownish-yellow coloration after a day or so of settling. Calcium carbonate was also quite effective as a flocculant for three of the five materials tested and sodium chloride was effective with two, but the supernatants remained cloudy with both chemicals. The organic chemicals p-benzoquinone, pyrogallol, polyvinyl alcohol, and krilium were not effective flocculants. Resorcinol was effective with only one of the dredged materials and the supernatant remained cloudy.

Based on the postulated flocculation criteria and the flocculation-dispersion mechanisms of each chemical, sodium hydroxide, potassium hydroxide, and sodium hexametaphosphate (Calgon) are good dispersing agents. Considering the initial sediment volume data and general observations, the higher percentages of organic substituted benzene ring compounds (7 millimole/m.e. or about 10 percent by weight of the solids) had a better flocculation effect than did the lower percentages of the same organic compounds. According to reports by the Dow Chemical Company (1969), their polymers Purifloc C-31 and Separon 273 are effective flocculants for dredging slurries at 0.4 to 20 grams per liter concentration; hence, these chemicals are promising flocculants for dredge overflow and weir overflow treatments. Because of the heterogeneous nature of the dredged materials and the relatively high concentration of solids (about 15%) in the slurry, the effectiveness of the organic polymers is not as good as might otherwise be expected. After studying the test results of this test program and comparing the engineering characteristics of the five dredged materials tested, it was found that the coarser dredged material are less affected by the selected additives. Therefore, the sedimentation-leaching test program was concentrated on the finer dredged materials treated mostly with inorganic chemical additives.

A comparison of the observed sediment volume versus time relationships for the 26 sedimentation samples suggests the following conclusions. For lime (CaO) treated samples the sedimentation process was shorter than for the non-treated samples. After 100% sedimentation, a more stable and larger sediment volume was formed; this is probably due to the flocculation and cementation effects of the lime. Sodium chloride (NaCℓ) treatment, on the other hand, led to inconsistent results, in one case there was no improvement at all, whereas in other cases some improvement was observed. Calcium chloride ($CaCl_2$) and resorcinol ($C_6H_4(OH)_2$) gave virtually no improvement in any case; this may be due to the fact that the chosen solids concentrations in the slurry were larger than the 50 grams per liter used in the flocculation-sedimentation tests.

Downward seepage forces would logically tend to densify dredged materials as leaching takes place, and the densities of the samples in the sedimentation-leaching tests were indeed found to be higher than those of the corresponding samples in sedimentation tests only. In addition, even though the treated samples had lower densities than the untreated samples in the sedimentation tests, they ultimately achieved higher densities when subjected to leaching. This suggests that the effects of seepage forces are greater than those of physico-chemical forces. The permeabilities of the lime, calcium carbonate, and sodium chloride treated samples were substantially higher (at least by an order of magnitude) than those of the untreated materials; this is evidently due to flocculation effects, which were insignificant for the other chemicals.

Shear strength and dry density were expected to increase as leaching approached completion and capillary tension became more effective. However, this was not the case for lime treated materials, which in all cases exhibited lower densities than untreated materials. At a water content of about 150 percent it was found that the cementation effect of the lime was too small to affect the shear strength, but at water contents of about 30 percent cementation substantially increased the strength of the same compacted material. Strength increase was approximately proportional to the amount of lime used. Calcium carbonate treatment resulted in a slight increase in the strength of compacted samples. Although sodium chloride acted as a compaction aid for promoting higher densities, it had a decreasing effect on strength **when** when compared with the results of untreated materials. This is perhaps due to the deflocculation effect at higher percentages of sodium chloride.

From twenty-two individual repeated leaching tests conducted on seven different materials with and without lime treatment, it was found that, for the lime-treated sediments, the volatile solids content of the leachates were higher than in the case of the untreated samples because of the greater removal of organics by calcium ions. Moreover, the total iron, potassium, and sodium ion concentrations of the leachates were lower than those of untreated materials; this may be due to an ion exchange by the calcium ions for certain organics. Since lime treatment introduced a larger amount of calcium ions in the leachates, the pH was increased to about 12 at the beginning of the test. The permeability increased by a factor of about ten relative to the permeability of untreated materials.

The durability of lime effects can also be evaluated to a limited degree from the results of this test program. After leaching with a volume of deionized water equal to three times the volume of the sediment, the calcium ion concentration in the leachate is about equal to that of the initial leachate sample from the untreated sediment; the pH value was also similar. However, the permeability and volume change of the sediments were affected to a small degree by the treatment; this may imply a basic change of the soil structure of the sediment by lime treatment.

In summary, among the many effective flocculants, calcium oxide and calcium chloride are the most suitable from the viewpoint of coloration and clarity of the supernatant. Upon studying the test results of this program and comparing the engineering characteristics of the five dredged materials tested, it was found that the coarser dredged materials were less affected by chemical additives. Based on an overall comparison of all chemical additives tested, lime appears to be the most effective additive; it has the ability to decrease the long-term volume change, increase the permeability, and retain some of the pollutants. Although the addition of lime causes a reduction in strength and an increase in the calcium ion concentration, it can alter the structure of the sediments favorably for further stabilization, such as compaction. The results of repeated leaching tests indicate that the leachates of chemically stabilized dredged materials do not constitute a very serious potential pollution hazard; in particular, if additives such as lime are used, the pollution potential will likely be reduced.

Evaporation

The effectiveness of dredging landfill operations and the utilization of dredged materials are strongly affected by their dewatering characteristics, and evaporation has been identified as an effective and economical means for accomplishing such dewatering. Pursuant to obtaining the soil-water potential of several typical dredged materials, three series of laboratory tests and two series of field evaporation tests were performed to investigate the effect of mixing, the influence of layer thickness and surface area, the effect of lime-treatment, and the influence of drainage conditions on the evaporative losses of water and the associated time-dependent gains in strength under the given climatic conditions. The resulting data are supplemented with information reported in several studies conducted by others, and appropriate conclusions are advanced.

Mixing or mechanical conditioning is one of the most important factors in accelerating evaporative losses; this is due largely to the fact that it destroys the dry crust that forms at the surface. However, conditioning apparently must be done on a more-or-less continuous basis. The initial rate of water loss due to evaporation increases with an increase in the initial water content of the slurry; this is probably due to a lowering of the flow resistance in the slurry with increasing values of water content. Decreasing the layer thickness greatly enhances the initial rate of water loss in the case of very thin layers (up to about 15 centimeters or 6 inches), but thicknesses in the range of several feet (as would likely occur in the field) apparently have little influence on the drying rate. Crack width in the laboratory tests apparently did not influence the evaporative losses very much; however, the increase in the exposed surface area due to crack formation in the field will almost certainly affect the drying rates, although no quantitative determinations can be made on the basis of available data. Lime treatment had no influence on the rate of water loss, but it increased the shear strength and reduced somewhat the associated volume changes, thereby indicating a change in the soil structure. These findings were more pronounced in the field tests than in the laboratory tests. The field test results show that there is no noticable strength reduction after lime treatment during rewetting. The effect of bottom drainage is still a quite substantial factor in the dewatering process and it should not be ignored, because some of the improvements in the engineering characteristics may be reduced by rewetting.

Transpiration

Plant transpiration may play an active role in stabilizing dredged materials at poorly drained areas on a long-term basis (about 5 years). However, climatic conditions, inundation, timing of spoil deposits, and seeding can not be easily controlled to assure the establishment and development of the planned plant communities in an active disposal area. Although transpiration is relative ineffective in enhancing the rate of water loss and strength increase on a short time basis, vegetation may provide wild life refuge and surface cover against erosion. Since stabilization by transpiration is relatively economical and simple, its advantages and disadvantages were evaluated, both as a supplemental method to combine with other stabilization methods and as the primary stabilization method. Described briefly herein are the major consequences of using vegetation to stabilize dredged spoil in diked containment areas.

Since vegetation growth increases the number and length of capillaries and the effective surface area through which water loss takes place, plants can transpire large quantities of water during the growing season. This water loss will continue long after the surface of the spoil has become dry. Therefore, vegetation can be used to dewater and partially consolidate dredged materials. Furthermore, due to the development of fibrous roots for binding soil particles, the shear strength of the rooted zone may be increased and soil erosion by water or wind may be decreased. However, the organic content of the spoil is obviously increased in the plant matter. Some plants (for example, bullrush) can take up organic toxic compounds and metabolize them into carbon dioxide and water; other plants readily accumulate metals in excess of the concentration in the soil. Large portions of these plants can be removed by timely harvest; mowing and harvest should also be used to remove most of the newly accumulated organic matter which might otherwise create higher organic content problems in later depositions.

Electro-osmosis

The particle size distribution and consistency of many dredged sediments suggests that electro-osmosis may offer one of the more suitable methods of stabilization, and an intensive laboratory study was directed toward evaluating the effectiveness of this method for dewatering and stabilizing dredged materials. Laboratory test results showed that electro-osmosis can dewater and consolidate these materials, producing a denser material with higher strength. An increase in the electrical gradient causes a substantial increase in the amount of fluid drained; the higher gradient produces its major effect in a shorter period of time than do lower gradients. The required current is decreased as the rate of fluid flow decreases. The values determined for the electro-osmotic coefficient of permeability are of the same order of magnitude as that which characterizes a large variety of soils (5×10^{-5} cm/sec per volt/cm).

The data indicated that a large portion of the change in dry density resulted from the applied consolidating pressure (0.6 kg/cm^2) and not from the electrical gradient. However, the increased average shear strength is apparently a result of the electrical treatment, probably due to its effects on soil structure and bond forces. As expected, there is a noticeable increase in the total solids content of the leachate as electrical gradients increased. The losses of ions from the sediments subjected to electrical treatment are reflected in gains for the same ions in the leachates, and the concentrations of these ions increase as the gradient increases. Notwithstanding the results of this laboratory test program, before application of electro-osmosis to an actual field problem it would be desirable to evaluate the power losses which occur in a comparable large-scale treatment process and the scaling factors associated with extrapolating these data to a field situation.

Vacuum Stabilization

Vacuum stabilization is best suited for stabilizing thick deposits (about 30 feet or more) of dredge spoil underlain by a permeable (sand) layer. The basic principle of this method is that the creation of a partial vacuum beneath the soft layer will help to consolidate this stratum by lowering the water table and increasing its effective weight and by adding a partial atmospheric pressure to the ground surface. In order to effectively employ this method, there must be a layer of pervious material in which to apply the vacuum, as well as a good seal on the surface to prevent loss of the vacuum. Although the vacuum system can greatly increase the rate of drainage of the dredged sediments, as well as improve the water content, dry density, and strength of the lower portion of the stabilized stratum, these improvements could be partially reversed by adverse hydraulic gradients in poorly drained areas with high water tables. Therefore, unless the subsurface conditions and other factors are appropriate, the vacuum stabilization method may not be economical.

Compaction

Although compaction is a common and easily controlled stabilization method, it is beneficial for stabilizing dredged sediments only when their in-situ water content approaches the optimum condition for compaction by the chosen equipment. The sediments must also have enough strength to support the compaction equipment. However, in the field the water content of the sediment is high (greater than 50%) and the strength is low (about 200 psf). If the in-situ water content of the sediment is controlled to be near optimum (about 30% for the materials tested) by other methods (evaporation, electro-osmosis, etc), compaction can be used to effectively improve the strength,density, and compressibility of the sediments. The engineering properties of compact dredgings can be further improved by treatment with 2% lime or cement prior to compaction.

Quicklime Piles

The quicklime pile method seems well suited for the conditions of dredged sediments in diked containment areas, because the hydration of quicklime results in a high volumetric expansion. The advantage of the quicklime system is that both reactants and products are readily permeable to water, thus, the reaction is able to proceed to completion and develop its full expansive force and it is not reversible. However, field investigation is needed to identify effective installation equipment and to evaluate the economic diameters and spacings of quicklime piles.

SUGGESTED STABILIZATION PROCEDURES

The problem of stabilizing dredged material that is deposited hydraulically into diked containment areas can be divided into two stages, namely, the sedimentation stage and the consolidation and drainage stage. The dredged material begins as a slurry with a water content of about 500% or 600%. One of the principal objectives of this investigation was to find a promising flocculant which will accelerate the sedimentation rate and cause more fine particles to settle from the slurry. If the sedimentation rate is increased, the size of the settling basin can be reduced. Similarly, if more fine particles settle from suspension, the quality of the effluent is improved. Lime was found to be one of the most promising additives to satisfy these objectives. The second stage begins after the sediment is formed. Although leaching of pollutants into the groundwater may be a problem in some cases, this will usually not be serious if a few feet (about 5 feet) of impervious clay is present below the sediment.

The stabilization of soft wet sediments to form a useful landfill constitutes the main thrust of this study. The recommended soil stabilization method depends largely on the projected use of the disposal site, the initial behavior of the dredged materials, and other conditions. Eight different stabilization methods were studied and found to be effective for dredged materials. However, freezing is a very specialized method that must be evaluated in greater detail, vacuum dewatering requires a special substratum, and plant transpiration is a long-term process. Therefore, suggested stabilization procedures are primarily concerned with how to utilize a combination of the five more suitable methods; these methods are chemical treatment, evaporation, compaction, electro-osmosis, and quicklime expansion pressure stabilization. A discussion of various solutions that are available for a typical problem is probably the best way to illustrate the application and effectiveness of each stabilization procedure, and this will be done in the following paragraphs.

Consider that a new fill will be used for a parking lot, residential construction, light industrial construction, or similar function requiring a medium to high level of strength. Assume that the dredged material is a clayey silt and that the diked area is located on low lying land with poor drainage. One possible sequence of proposed stabilization procedures might be:

1. Design the required size and configuration of subdikes or separate dikes on the basis of laboratory sedimentation rates for lime-treated slurries; from the field evaporation test data determine the optimum thickness of the lift and the exposure time required to obtain the desired strength gain.

2. The required number of subdikes can be determined from the data on slurry concentration and discharge rate; the slurry is deposited in the areas enclosed by the subdikes and the bottom of each subdike area should be kept level.

3. About 2% lime (by weight) is added to the slurry during the discharge process; this lime treatment will increase the sedimentation rate, increase the permeability, and improve the initial structure of the sediment. Lime induced flocculation also results in a greater removal of solids from the supernatant.

4. Good bottom drainage is not important (as long as there is no adverse hydraulic gradient, e.g. upward flow), since the dewatering is by evaporation; however, good surface drainage is necessary, since most of the suspended solids are removed by lime treatment, a weir, rather than an elaborate filtering system, should suffice to remove the effluent from each subdiked area.

With this stabilization procedure the site will be suitable for the assumed uses immediately after the last lift has dried and reached the desired strength. It is important to realize that the size of subsequent subdikes, the optimum thickness of the lifts, and the exposure times for for each lift to undergo evaporation should be corrected as field sedimentation rate data and field evaporation data are accumulated during the initial stages of the disposal process.

Alternate stabilization procedures for the same assumed conditions might be:

1. Provide surface and bottom drainage by constructing filter dikes and a bottom drainage blanket.
2. Install vertical perforated aluminum pipes and fill with sandy material; these will reduce the drainage paths in the fill for the escape of water and gases.
3. After the diked containment area is filled with sediment, use the aluminum pipes as electrodes for electro-osmotic stabilization. If the electrode reversal method is used, the clogging of the sandy material in the pipes may be reduced. The preloading effect of the upper part of the fill on the lower part is combined with the electro-osmotic effect to improve the engineering characteristics (strength and deformability) of the lower portion. Furthermore, a hardening effect may be induced due to corrosion of the aluminum electrodes.
4. After the electro-osmotic process is complete, the water content of the upper portion of the fill can be reduced to attain a low to medium level of strength at which stage compaction may be used to improve the strength and deformability characteristics of the upper layer.

If all these steps are applied to the dredged sediment, the landfill will be ready for use immediately after compaction is completed. Since the dredged slurry in this example was not treated with lime, filter dikes or some filter system may be necessary to remove excessive suspended solids from the effluent. The disposal process is not scheduled to fully mobilize evaporation effects and electro-osmosis and compaction are therefore necessary to densify the sediments and improve their strength and deformability characteristics. It is important to emphasize that the suggested procedure is a preliminary estimate based on the literature and laboratory test results; the actual specification should be based on accumulated field test data.

Still a third potential stabilization procedure for an existing fill with essentially the same other conditions as the assumed problem might be:

1. Since there is no drainage blanket below the fill and since there are no filter dikes enclosing the containment area, it is reasonable to assume that a two to three foot thick crust will form on the surface due to evaporation.
2. After this crust has formed, install quicklime piles in the existing fill. Due to expansion during hydration, the quicklime exerts a high pressure on the surrounding sediment and lateral consolidation is induced. Furthermore, the products of the lime hydration are readily permeable to water and serve as drainage piles in the fill. This combination of drainage and preloading effects (from the weight of the upper part of the fill) will serve to consolidate vertically the lower part of the fill.
3. After the drainage and consolidation process is complete, the upper part of the fill may have a low to medium strength level; then, compaction can be used to improve the strength and deformability characteristics of this portion of the fill.

In this example the determination of the actual diameter of the lime piles, the spacing and pattern of the piles, and the installation procedure require field investigation. The landfill will be ready for use immediately after completion of compaction.

Finally, if not economically feasible, none of the above mentioned processes might be used. If an adequate vegetative cover can be provided, the transpiration effect can dewater and adequately densify the top few feet of the fill. After about two years, the site can be used for recreational parks, agricultural land, or wild life refuges. In addition, if the site does not have a water source (river or lake) and if there exists a thick sand layer below the soft substratum, vacuum dewatering method may be useful to stabiliaing both the dredged sediments and the soft substratum.

CHAPTER 12

CONCLUSIONS AND RECOMMENDATIONS

The disposal of dredged materials in diked containment areas causes potential problems associated with (a) surface water pollution by effluents from the diked areas, (b) groundwater pollution by leachates from the sediments within the diked enclosure, and (c) stabilization of the soft sediments. In order to isolate these problems and treat them separately, two stages in the deposition history of hydraulic placed dredged spoil are considered. In the first stage the dredged material is a slurry with about 10% to 20% solids concentration (about 400% to 800% water content), and surface water pollution is the main concern. In the second stage the dredged material is a soft, wet sediment with a water content of about 100% or somewhat higher, and the main concerns during this stage are the leachate pollution problem and the stabilization problem.

Pursuant to the background developed in Chapters 1 through 4, the principal thrust of Chapter 5 (flocculation and sedimentation) is directed toward the solution of the surface water pollution problem, and Chapter 7 (repeated leaching) deals primarily with the potential pollution of the groundwater by leachates; Chapter 6 (sedimentation-leaching) serves as a bridge to interrelate the preceding two chapters, as well as to establish some of the data pertaining to stabilization. Chapters 8, 9, and 10 discuss methods of stabilizing the sediments to form a useful landfill, and Chapter 11 synthesizes the results of the overall study.

CONCLUSIONS

In general, a diked containment area will serve as an excellent solids-liquid separation device; however, if an effective flocculant is mixed with the dredging slurry, the sedimentation rate is increased and more fine particles are removed from the supernatant. Accordingly, either the size of the retention basin can be reduced or several subdiked areas can be used in cycles to take full advantage of natural evaporation effects. After studying a large number of different chemical additives, lime (CaO) was found to be one of the most promising, since it not only flocculates the solid particles, but also stabilizes the initial structure of the sediment by increasing its permeability and decreasing its long-term volume change. This effect provides a good basis for future stabilization of the sediment. Because of the heterogeneous nature and high concentration of the dredging slurry, the more sophisticated chemical reactions are not easily controlled; therefore, organic flocculants are not generally recommended. Due to the fertility of many dredged sediments, especially in watersheds containing agricultural areas, a cover of natural vegetation can be easily established. This provides good protection of the surface against errosion and reduces the surface water pollution on a long-term basis. Therefore, if adequate precautions are taken, the problem of surface water pollution can be minimized.

Logically, it would seem that any external aid to increase the dewatering rate of the sediments should cause more contamination of the leachate. However, chemical analyses of the leachates from laboratory drainage tests, electro-osmosis tests, and slurry consolidation tests all show that the contaminants are of the same order of magnitude as those from gravity-induced repeated leaching tests. Therefore, based on these data and related discussions in the literature, it may be concluded that leachates from dredged spoil in a diked containment area do not appear to cause any serious pollution problem. This is due in large part to the fact that the permeability of most clayey or silty dredged sediments is very low, the underlying soil has a natural ability to remove many contaminents, and the ground water is able to adequately dilute the relatively small amounts of contaminants that are leached from the solids. If a few feet of impervious clay is present under the sediments, as is frequently the case, the leachate pollution problem, can be virtually prevented.

The effective stabilization of dredged sediments in diked containment areas poses a particularly challenging problem to the engineer. Since confined disposal sites are often located in low lying swampy areas with poor drainage and reversible rewetting effects, some conventional soil stabilization methods are rather ineffective. Furthermore, because of the soft, wet character of the sediments, various other soil stabilization methods cannot be easily applied. Cognizant of these factors and considering the ultimate usefulness of the landfill, the following conclusions from the investigation of stabilization methods can be advanced:

1. The introduction of lime into the dredged material slurry causes flocculation of the solid particles and produces a more open and stable soil structure in the sediment; thus, the permeability and long-term volume change characteristics are improved. However, the shear strength of the sediment may not improve and the permanence of some improvements may be partially lost by continuous leaching. Moreover, lime treatment is conducive to the removal of some organics in the sediment through ion exchange during the leaching process.

2. Mixing or mechanical conditioning can effectively accelerate the evaporation rate, but the effect may be partially offset by inadequate drainage. However, by using an effective flocculant to increase the sedimentation rate, constructing subdikes to control the thickness of lifts, and providing adequate drainage, the dredged sediment can be stabilized at a reasonable cost.

3. Evaporation alone, (without mechanical conditioning), can improve somewhat the engineering properties of the dredged materials, but its effectiveness is reduced by the formation of a crust, thereby impeding subsequent evaporation.

4. The establishment of a vegetation cover cannot produce significant improvement on a short-term basis, but it offers a simple, economical, and non-disruptive long-term method for partially stabilizing existing landfills of dredged sediments.

5. Electro-osmosis offers one of the better techniques for stabilizing dredged sediments with the particle size distribution and consistency normally encountered. The method is more expensive than the use of subdikes, flocculation, adequate drainage, and evaporation, but a better controlled and higher quality landfill can be obtained. If aluminum electrodes are used, the electro-chemical effects will not be reversible after rewetting.

6. The employment of quicklime piles is also expensive, but a better quality landfill can be obtained and the effect of quick lime hydration is not reversible; this method is most suitable for stabilizing existing landfills.

7. In order to be feasible, compaction requires that the sediment possess some initial supporting strength this seriously limits its usefulness for dredged material landfills unless special provisions are taken to dewater or condition the spoil prior to compaction.

8. Vacuum stabilization appears to be most applicable for stabilizing thick deposits of dredged materials or possibly both the deposit and the underlying soft soil layers, provided there is a permeable sand layer beneath these layers and the area is isolated from sources of water.

9. If the disposal site can be located at a relatively high elevation, gravity drainage can be used to advantage and many of the stabilization problems can be avoided.

RECOMMENDATIONS

Based on the results of an intensive laboratory study and an extensive literature review, the relative importance of each parameter, such as sedimentation rate, permeability, density, etc., on the stabilization of dredged material has been evaluated; the primary need at this time lies in the accumulation of appropriate field data to verify or modify the concepts that have been advanced. Some specific recommendations emanating from this investigation are:

1. Continue to explore the possible availability of promising flocculating agents.
2. Develop standardized test procedures for evaluating the effectiveness of various additives in terms of both stabilization benefits and long-term pollution potential.
3. Conduct an intensive field test program to assess more comprehensively the potential environmental hazard associated with leachates from dredged materials and develop a mathematical and/or physical model to enable the extrapolation of the results obtained.
4. Undertake a more extensive study of possible contaminants, such as organic materials, heavy metals, etc., and biological constituents that might affect the pollution potential of leachates from dredged materials.
5. The field sedimentation rate of lime treated slurries should be determined before the size and number of subdikes can be specified with any degree of confidence.
6. Full scale field evaporation tests should be performed to evaluate the absolute, rather than relative, significance of the laboratory and small scale field tests conducted as part of this study.
7. A field evaluation of electro-osmotic stabilization is necessary to determine energy requirements and the optimum pattern and spacing of electrodes, and thereby the economical feasibility of the method; special attention should be focused on the irreversible hardening effect of corrosible alluminum electrodes.
8. The optimum diameter, spacing, and pattern of quicklime piles, as well as the availability of special equipment for installation, must be studied before field application can be undertaken.
9. A quantitative evaluation of the effectiveness of certain specific types of vegetation for dewatering and stabilizing dredged sediment should be made and some promising species should be identified.
10. Study the possibility of using the natural freezing phenomenon to (a) induce a temperature gradient and translocate water upward from lower portions of the dredged material deposit and (b) reduce the biological activity in the sediments.

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